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CRETACEOUS NANNOFOSSIL STRATIGRAPHY AND PALEOECOLOGY OF THE CANADIAN ATLANTIC MARGIN

P.H. DOEVEN

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Preface

Since the first well was drilled on the Scotian Shelf in 1966, geologists have been using microfauna present in the cores to subdivide and correlate subsurface sediments of the area. These biostratigraphic studies of the Atlantic Margin, however, have focused on foraminifera and dinoflagellates but little information has been available on calcareous nannofossils. Nannofossils are used for these studies because their minute size allows optimum use of sidewall cores and cutting chips and their detailed zonation improves the stratigraphic framework established with either foraminifera or dinoflagellates.

In this study, the first comprehensive treatment of Cretaceous nannofossils from the Canadian Atlantic Margin, the author proposes a new nannofossil zonation to correlate rocks of Albian through Maastrichtian age found in seventeen offshore wells. Such correlations are necessary if the geology of the East Coast of Canada is to be better understood, thereby enabling more precise estimates to be made of our oil and natural gas resources.

R.A. Price
Director General
Geological Survey of
Canada

OTTAWA, September 1982

Préface

Depuis le moment où, en 1966, le 1er puits était foré sur le plateau continental Scotian, les microfaunes présentes dans les carottes ont aidé les géologues à établir la subdivision et la corrélation des sédiments sous-marins de la région. Cependant, ces études biostratigraphiques de la marge de l'Atlantique ont porté plus particulièrement sur les foraminifères et les dinoflagellés tandis que peu de renseignements étaient recueillis au sujet des nannofossiles calcaireux. L'intérêt que présentent les nannofossiles pour ce genre d'étude vient du fait que leur taille miniscule permet l'utilisation optimale des carottes prélevées sur la paroi latérale des puits et des débris de forage, et que la disposition détaillée des zones ajoute au cadre stratigraphique déjà établi à l'aide des foraminifères ou des dinoflagellés.

Dans la présente étude, soit le premier traitement d'ensemble des nannofossiles crétacés de la marge canadienne de l'Atlantique, l'auteur propose l'existence d'une nouvelle distribution des zones des nannofossiles servant à établir la corrélation entre les roches dont les âges varient de l'Albien au Maestrichtien et provenant de 17 puits forés au large des côtes. Une meilleure compréhension de la géologie de la côte Est du Canada demande que l'on établisse de telles corrélations, de façon à permettre l'évaluation plus exacte des ressources canadiennes en pétrole et en gaz naturel.

R.A. Price
Directeur général
Commission géologique
du Canada

OTTAWA, le 19 septembre 1982

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CRETACEOUS NANNOFOSSIL STRATIGRAPHY AND PALEOECOLOGY OF THE CANADIAN ATLANTIC MARGIN

Abstract

Using both conventional and probabilistic techniques, a 16-fold nannofossil zonation has been erected to correlate Albian through Maastrichtian rocks in 17 wells, offshore eastern Canada. The zonation uses four types of stratigraphic events: lowest occurrence, lowest consistent occurrence (subbottom), highest consistent occurrence (subtops), and highest occurrence.

The proposed nannofossil zonation compares closely to previous zonations and is consistent with standard planktonic foraminiferal stratigraphy as applied in three of the wells studied. Discrepancies at stage level exist with regional palynomorph and foraminiferal "assemblage" zonations. A regional hiatus occurs at the Cretaceous-Tertiary contact, varying in duration from 2 to 25 Ma. Several local hiatuses were detected in the Upper Cretaceous sequence that may be related to salt tectonism.

The main periods of limestone deposition were in Turonian (Petrel Member) and Late Santonian through Early Maastrichtian (Wyandot Formation) time. The relative abundances of *Lucianorhabdus cayeuxii*, as calibrated with regional facies analysis in the Danish Embayment, indicate that the chalk in the Wyandot Formation was deposited in an outer shelf environment. Chalk sedimentation took place at an average rate of 1.5-2 cm/ka.

An increase in the frequency ratio of *Micula "staurophora"* s.l. versus *Watznaueria barnesae* and increasing abundance of *Arkhangelskiella cymbiformis* and *Kamptnerius magnificus* suggest Early Maastichtian cooling. This event, and the coeval offshore shift in carbonate deposition may be related to a change in ocean circulation pattern caused by early seafloor spreading in the Labrador Sea.

Résumé

Des méthodes classiques et probabilistes ont permis d'établir une zonation de nannofossiles à 16 unités pour la corrélation des roches de l'Albien au Maestrichtien dans 17 puits au large de la côte Est du Canada. Cette zonation est fondée sur quatre types d'événements stratigraphiques: présence inférieure, présence régulière inférieure (sous-base), présence régulière supérieure (sous-sommets) et présence supérieure.

La zonation proposée de nannofossiles se compare de très près aux zonations antérieures et se conforme à la stratigraphie foraminifère planctonique classique, comme appliquée à trois des puits étudiés. Il y a divergence d'étages dans les zonations régionales d'"assemblages" de palynomorphes et de foraminifères. Une lacune régionale existe au contact Crétacé-Tertiaire; sa durée varie de 2 à 25 Ma. Plusieurs lacunes locales ont été décelées dans la séquence du Crétacé supérieur; elles pourraient être liées à l'halocinèse.

Le calcaire s'est accumulé principalement durant le Turonien (niveau Petrel) et du Santonien récent au Maestrichtien ancien (formation de Wyandot). L'abondance relative de *Lucianorhabdus cayeuxii* par rapport à l'analyse des faciès régionaux dans le rentrant Danish indique que la craie de la formation de Wyandot s'était accumulée sur une plateforme extérieure. La vitesse moyenne d'accumulation de la craie était de 1,5 à 2 cm/ka.

Une augmentation de la raison de fréquence de *Micula "Staurophora"* s.l. par rapport à *Watzenaueria barnesae* et l'abondance accrue d'*Arkhangelskiella cymbiformis* et de *Kamptnerius magnificus* laissent supposer qu'il y a eu refroidissement durant le Maestrichtien ancien. Cet événement, ainsi qu'un déplacement contemporain de la sédimentation carbonatée au large des côtes, pourrait être lié à une modification du modèle de circulation des courants, provoquée par l'expansion du fond de la mer du Labrador.

INTRODUCTION

Since 1966 numerous exploratory wells have been drilled on the Scotian Shelf, Grand Banks and Labrador Shelf, which together make up the southern part of the Canadian Atlantic margin. Biostratigraphic publications on these wells have focused mainly on foraminifera and dinoflagellates, as published information on calcareous nannofossils in this area is meager. Upshaw et al. (1974) listed some nannofossil species for the Upper Tertiary, Lower Tertiary, Upper Cretaceous, and Lower Cretaceous of some wells on the Grand Banks. Williams et al. (1974) proposed six nannofossil zones for the Upper Cretaceous of the Shell Naskapi N-30 well.

This paper is the first comprehensive treatment of Cretaceous nannofossils from the Canadian Atlantic margin. This report, which was completed at the Atlantic Geoscience Centre in Dartmouth, Nova Scotia, under the Visiting Fellowship Program of the Natural Sciences and Engineering Research Council of Canada, discusses:

1. The application of nannofossils to high resolution stratigraphy in Albian-Maastrichtian deposits along the Canadian Atlantic Margin;
2. Albian-Maastrichtian nannofossil zonations and their correlation with other microfossil zonations;
3. The application of probabilistic methods to regional nannofossil stratigraphy;
4. The geographical and stratigraphical distribution patterns and paleoecology of Late Cretaceous nannofossils in the northwestern Atlantic; and
5. The distribution of Upper Cretaceous chalk deposits offshore eastern Canada.

Figure 1. Location of the offshore wells, Canadian Atlantic margin.

Material has been studied from the following wells (Fig. 1):

Scotian Shelf. Shell Mohawk B-93, Shell Triumph P-50, Shell Onondaga E-84, Shell Primrose A-41, Shell Mississauga H-54, Shell Mic Mac H-86, Shell Wyandot E-53, Petrocanada Shell Moheida P-15, Shell Mobil Tetco Eagle D-21, Mobil Tetco Sachem D-76, and Mobil Tetco Gulf Adventure F-80;

Grand Banks. Amoco Imp Heron H-73, Amoco Imp Skelly Osprey H-84, Elf et al. Emerillon C-56, and Mobil Gulf Adolphus D-50;

Labrador Shelf. B.P. Columbia et al. Indian Harbour M-52.

In this paper depths are quoted in feet, maintaining the original quotations used in the Well History Reports (Open File, Department of Energy, Mines and Resources, Dartmouth, N.S.) and in the well sample collection of the Geological Survey of Canada. All depths are below rotary table. Six plates illustrate the principal nannofossil taxa used (GSC No. 69319-69358).

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I would like to thank Felix Gradstein for making this project possible, for valuable discussions on the (bio)stratigraphy and paleoecology of the northwestern Atlantic margin and on biostratigraphic methods, for providing unpublished foraminiferal data, and for critically reading the manuscript; Tony Jenkins for his constructive criticism of the manuscript; Marie-Pierre Aubry for her guidance in the identification of Paleogene nannofossil species; Lubomir Jansa and John Wade for providing and discussing lithostratigraphical and sedimentological data; Frits Agterberg for discussions on probabilistic stratigraphic methods; Katharina Perch-Nielsen for helpful criticism; Graham Williams for providing and discussing palynological data; and the Geological Survey of Canada and the Natural Sciences and Engineering Research Council of Canada for the opportunity to undertake this project.

Regional Geology

The Canadian Atlantic margin can be divided into the Scotian Shelf, Grand Banks, and Labrador Shelf (Fig. 1). Basement consists of igneous and metasedimentary rocks, ranging in age from Precambrian to late Paleozoic. The Mesozoic-Cenozoic sedimentary wedge has a maximum thickness of 10 to 12 km on the Scotian Shelf, northern Grand Banks, and Labrador Shelf, and about 6 km on the southern Grand Banks.

Sedimentation on the Scotian Shelf and Grand Banks initially took place in a continental environment during the Triassic and Early Jurassic. During the Late Jurassic, shallow marine clastic and carbonate rocks and deltaic sediments accumulated, presumably in conjunction with the opening of the Atlantic Ocean. A Mid-Cretaceous marine transgression led to the deposition of fine grained clastic and chalky carbonate rocks. This situation persisted into the Late Oligocene, when a regional marine regression commenced that culminated at the end of the Pliocene in glacial and periglacial conditions.

On the Labrador Shelf nonmarine to marginal marine sediments and volcanic rocks were deposited locally in the Early Cretaceous. Open marine conditions were established during the Late Cretaceous.

A generalized stratigraphic column for the Canadian Atlantic margin (after Purcell et al., 1980) is shown in Figure 2. The Triassic and Lower Jurassic Eurydice, Argo, and Iroquois formations consist of continental redbeds and evaporites. The salts of the Argo Formation are mobile and form numerous diapiric structures. The Jurassic Mohican Formation comprises continental clastic rocks. The Jurassic to Lower Cretaceous MicMac, Abenaki, and Verrill Canyon formations comprise, respectively, a nearshore shale-sandstone and carbonate sequence, shelf-edge carbonates, and basinal shales.

The Lower Cretaceous Missisauga and Logan Canyon formations are predominantly sandstone sequences deposited in a deltaic system. Purcell et al. (1980) recognized three members within the Logan Canyon Formation: the Naskapi and the Sable members (both local shale tongues), and the Eider Member (a sand-shale sequence on the Grand Banks). The Shortland shale is a lateral (seaward) correlative of the Logan Canyon Formation.

On the Scotian Shelf and Grand Banks the Logan Canyon Formation and the Shortland shale grade upwards into the Dawson Canyon Formation, which consists of shales occasionally with thin beds of siltstone, sandstone, and limestone. A regionally persistent limestone has been named the Petrel Member. The Dawson Canyon Formation is overlain by the Wyandot Formation, consisting of chalk, interbedded with marls and calcareous shales. The carbonate rocks are coarser grained in the higher shelf areas and more frequently interbedded with marls near the present shelf edge.

The Banquereau Formation overlying the Wyandot Formation is a sequence of predominantly mudstone with subordinate beds of sandstone and marl. Locally it contains thick sandstone beds, especially in the Paleocene-Eocene and the Miocene, and carbonate beds. The Quaternary Laurentian Formation consists of glacial and periglacial deposits.

On the Labrador Shelf the Lower Cretaceous comprises volcanic rocks (Alexis Formation), sandstone (Bjarni Formation) and, locally, shale and coal beds (Snorri Member). These are unconformably overlain by the Upper Cretaceous to Lower Paleogene Cartwright Formation, which comprises marine and nonmarine mudstones and shales and, locally, marginal marine sandstones (Freydis Member and Gudrid Member).

The top of the Labrador sediment succession consists of monotonous turbiditic mudstone of the Saglek Formation, which includes the sandy unit of the Leif Member, and unnamed unconsolidated Pliocene-Pleistocene sands and clays.

The geology of the Canadian Atlantic margin has been described in detail by McIver (1972), Jansa and Wade (1975 a,b), Given (1977), Umpleby (1979), and Purcell et al. (1980). The above summary is derived from these publications. Most formal lithostratigraphic units of the Scotian Shelf and Grand Banks were defined by McIver (1972). The nomenclature for the Labrador Shelf is after McWhae and Michel (1975) and Umpleby (1979).[1]

[1] After completion of this manuscript a revised and more refined subdivison of the Labrador Shelf sequence was proposed by McWhae et al. (1980).

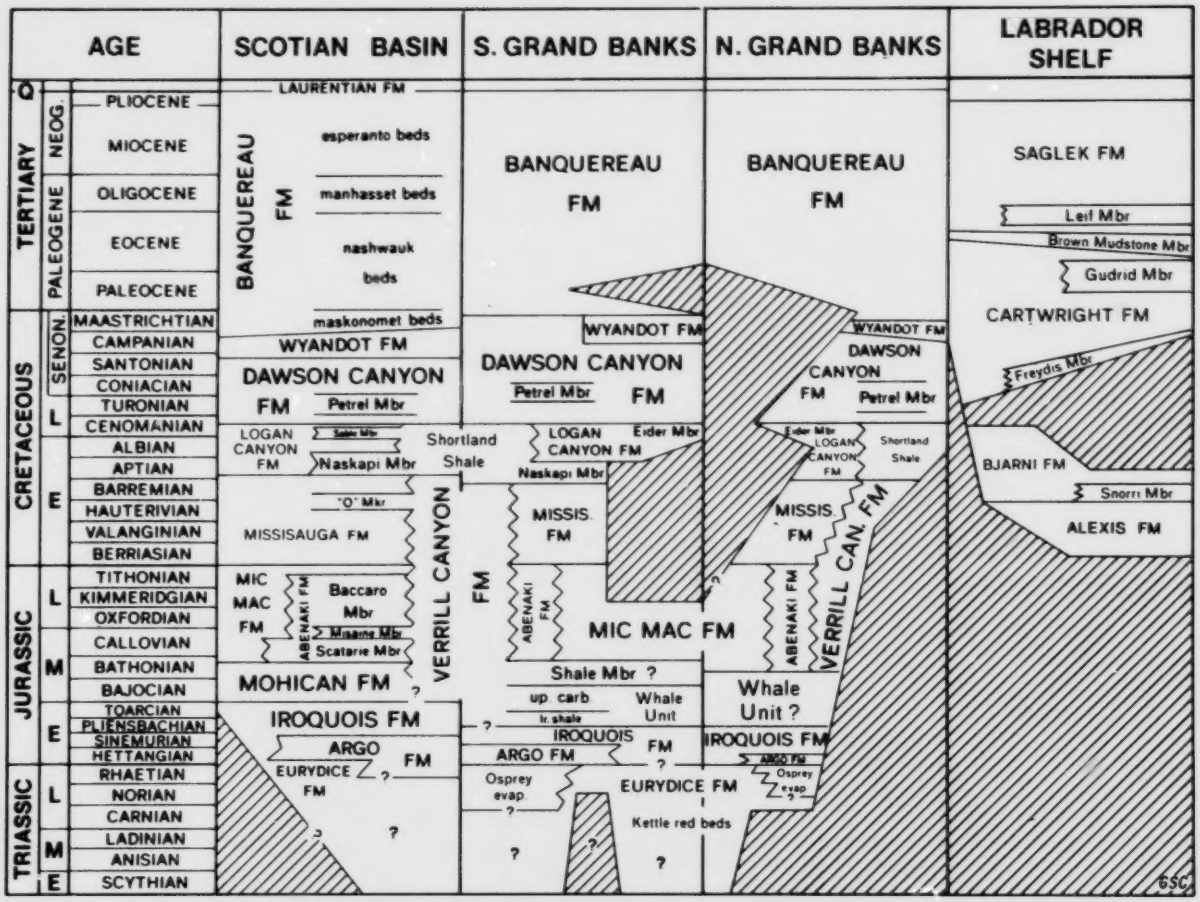

Figure 2. Generalized stratigraphic columns for the Mesozoic and Cenozoic successions of the Scotian Shelf, Grand Banks and Labrador Shelf (modified after Purcell et al., 1980).

Nannofossils generally occur in large numbers in the shales, chalks, and marls of the Albian-Maastrichtian interval, but are scarce or lacking in the coarser clastic rocks of the Albian-Turonian interval. In the chalks they are poorly preserved owing to the secondary overgrowth of calcite. In other sediments preservation generally is good, with occasional signs of dissolution.

Methods

In this study smear slides prepared from sidewall cores, ditch cuttings, and some conventional cores, were analyzed under a simple Leitz polarizing microscope equipped with a lambda 1 compensator. Selected samples were also examined with the Cambridge S160 scanning electron microscope.

Sidewall cores and conventional cores were studied whenever possible. Ditch cuttings (30 foot composite samples) were used to compensate insufficient or lacking sidewall core and conventional core coverage. Composite ditch cuttings as well as individual rock fragments from the cuttings were examined. By comparing the nannofossil assemblages of several individual rock fragments from a single ditch cuttings sample it was often possible to recognize and disregard caved rock fragments. The type of sample used from each of the wells studied is shown in Table 1.

In attempting to understand biogeographical and paleoecological patterns, the relative frequency of nannofossil species was determined in 30 samples from the Campanian-Maastrichtian interval, based on counts of 400 specimens per sample (200 in the centre of the slide, 200 along the margin).

Photomicrographs were taken with a Leitz Orthomat camera attached to a Leitz Orthoplan microscope.

Table 1: Type of samples examined in studied wells. Dot indicates well with only a few samples analyzed.

WELLS	CORES	SIDEWALL CORES	CUTTINGS
MOHAWK B-93		★	
TRIUMPH P-50		★	
ONONDAGA E-84		★	★
PRIMROSE A-41	★	★	
MISSISAUGA H-54		★	★
MIC MAC H-86		★	★
WYANDOT E-53		★	★
MOHEIDA P-15•			★
EAGLE D-21•	★		
SACHEM D-76•		★	★
ADVENTURE F-80•		★	
HERON H-73			★
OSPREY H-84			★
EMERILLON C-56•			★
ADOLPHUS D-50		★	★
INDIAN HARBOUR M-52			★

GSC

BIOSTRATIGRAPHY

The biostratigraphic framework developed for the Albian- Maastrichtian of the Canadian Atlantic margin embodies a sequence of nannofossil datum horizons, defined by the lowest occurrences (entries, bases) and highest occurrences (exits, tops) of nannofossil species.

Nannofossils are minute (usually smaller than 15 ^{e}m) and hence susceptible to reworking. Lowest occurrences therefore are generally considered more reliable than highest occurrences.

The biostratigraphic scheme presented here (Fig. 3) combines conventional (subjective) and quantitative (probabilistic) methods. The conventional method involves the establishment of a biostratigraphic subdivision (zonation) mainly based on the stratigraphically most continuous well sections. The quantitative approach consists of a computer-operated probabilistic ranking and scaling of biostratigraphic events, based on as many well data as possible.

The zonation in the left-hand column of Figure 3 resulted from the conventional biostratigraphic approach. The order of events in the right-hand column was determined in the quantitative analysis. The ranking of these events is an average of the observed sequences of events in ten wells. The probabilistic analysis maintained the order of the zone markers as established in the conventional approach.

I have aimed at constructing a flexible biostratigraphic scheme rather than a rigid zonation. Several of the nannoplankton datums used in this framework are well known, globally recognizable events, that can be related to existing zonations and that permit chronostratigraphic calibration. Other events can be used when zone markers are not found or recognized owing, for example, to sample spacing or poor preservation, or in attempting greater biostratigraphic refinement. The scheme shows the general sequence of nannofossil events; each event is not necessarily recognizable or useful in every well.

The biostratigraphic zonation is presented in Figure 4 and is compared with five recently published Upper Cretaceous nannofossil zonations. Manivit et al. (1977) summarized the results of the nannoplankton session of the Congress on Mid-Cretaceous Events in Nice 1976 (IGCP Project 50). Data are from the stratotypes, from sections in France, Spain, and Tunisia, and from DSDP sites. Martini's (1976) zonation was developed for DSDP Leg 33 (central Pacific) and was also used by Schmidt (1978) for Leg 44 (west Atlantic). Roth's zonation (1978) was largely compiled from published data, with an emphasis on deep sea sections. Verbeek's (1977) zonation is based on sections studied in Tunisia, France (including stratotypes), and Spain. Sissingh (1977, 1978) based his zonation on data from Tunisia, France, northwest Europe, western Asia, and New Jersey (data include Cretaceous stratotypes). The biostratigraphic zonation proposed here incorporates elements from all these zonations. It is discussed below in ascending stratigraphic order.

Albian-Turonian

Prediscosphaera Columnata Zone Thierstein 1971, nom. corr. Manivit et al. 1977

Definition: The interval from the lowest occurrence of *P. columnata* to the lowest occurrence of *Eiffellithus turriseiffeli*

Age: Middle Albian

Remarks: Roth (1978) and others make no distinction between *Prediscosphaera cretacea* and the smaller *P. columnata*. The *P. columnata* Zone was encountered only in the Adolphus D-50 well.

Eiffellithus Turriseiffeli Zone Thierstein 1971, emend. Manivit *et al.* 1977

Definition: The interval from the lowest occurrence of *E. turriseiffeli* to the lowest occurrence of *Lithraphidites acutum*

Age: Late Albian to middle Cenomanian

Remarks: *Hayesties albiensis*, used by Manivit et al. (1977) to subdivide the *E. turriseiffeli* zone, was not found in the Canadian offshore. Instead the highest occurrence of *Watznaueria britannica* is used to subdivide this zone. I have arbitrarily placed the Albian-Cenomanian boundary at the exit level of *W. britannica*, in accordance with the range given by Thierstein (1976) for this species. On the Atlantic continental margin the lowest occurrence of *Microrhabdulus decoratus*, a zone marker used by Sissingh (1977), appears to

Figure 3. Proposed Albian-Maastrichtian nannofossil zonation for the Canadian Atlantic margin.

be situated between the exit of *W. britannica* and the entry of *Lithraphidites acutum*. Manivit et al. (1977) and Verbeek (1977), however, recorded the entry of *M. decoratus* above the entry of *L. acutum*.

Litharaphidites acutum Zone Verbeek *in* Manivit et al. 1977

Definition: The interval from the lowest occurrence of *L. acutum* to the lowest occurrence of *Quadrum gartneri*.

Age: late Cenomanian

Remarks: Useful datum horizons within this interval are the highest occurrence of *Cruciellipsis chiastia*, the highest regular occurrence of *Corollithion completum* and the lowest occurrence of *Gartnerago obliquum*. *C. chiastia* has also been used as a subzone marker by Manivit et al. (1977). In the Canadian offshore *C. completum* is a characteristic constituent of Cenomanian to lowermost Turonian assemblages. Although some rare specimens of this species were found in the Upper Campanian and Maastrichtian in some wells, *C. completum* generally disappears in the Upper Cenomanian, between the exit of *C. chiastia* and the entry of *G. obliquum*. The position of the exit of *C. completum* in the probabilistic sequence relative to the entry of *G. obliquum*, however, is not well defined. The lowest occurrence of *Gartnerago obliquum* has been used as a zone marker by Verbeek (1977) and Roth (1978).

Quadrum gartneri Zone Cepek and Hay 1969a nom. corr. and emend. Manivit et al. 1977

Definition: The interval from the lowest occurrence of *Q. gartneri* to the lowest (regular) occurrence of *Eiffellithus eximius*

Age: Early Turonian

Remarks: I have arbitrarily placed the Cenomanian-Turonian boundary at the base of this zone in agreement with Sissingh (1977, 1978). Manivit et al. (1977), and Roth (1978) put this boundary somewhat lower, whereas Verbeek (1977) positioned it somewhat higher. The highest occurrence of *Podorhabdus albianus* appeared to be at approximately the same level as the lowest occurrence of *Q. gartneri*, in some wells just above this level, in other wells just below. The entry of *Lucianorhabdus maleformis*, a marker species of Sissingh (1977), is situated within this zone.

Eiffellithus eximius Zone Verbeek 1976b emend. Manivit *et al.* 1977

Definition: The interval from the lowest (regular) occurrence of *E. eximius* to the lowest occurrence of *Marthasterites furcatus*.

Age: Late Turonian

Remarks: The entries of *Micula decussata*, *Kamptnerius magnificus* and *Ahmuellerella octoradiata* occur within this interval. Their relative order in the probabilistic sequence.

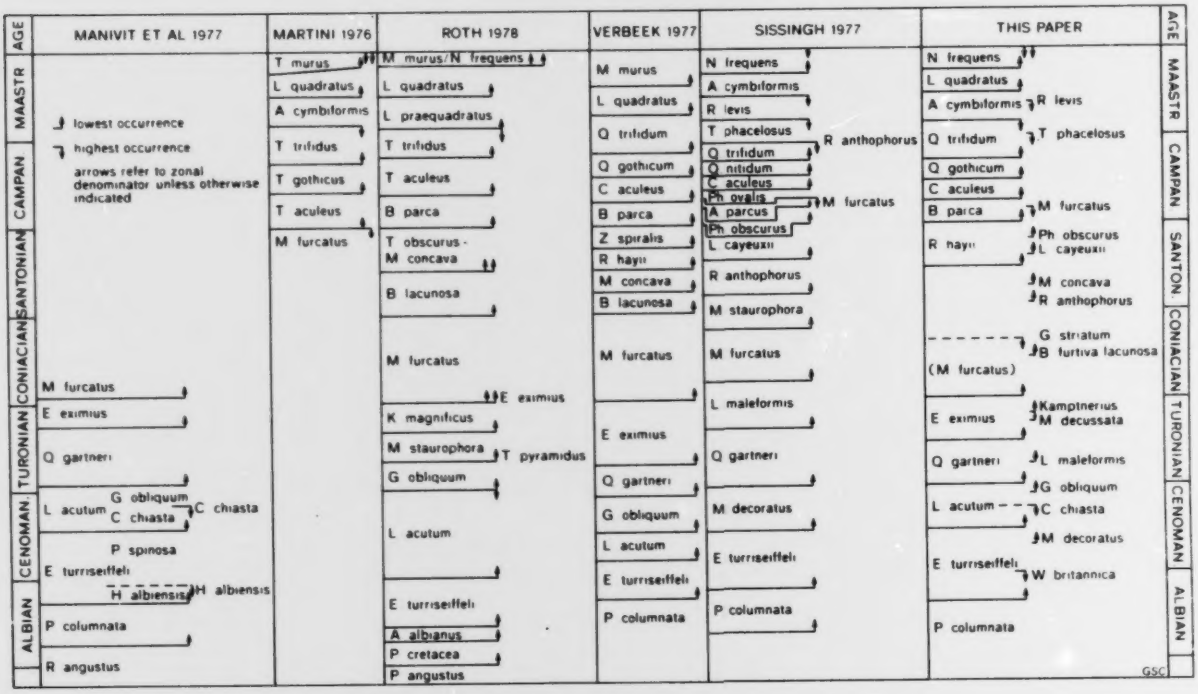

Figure 4. Comparison of Albian-Maastrichtian nannofossil zonations.

however, is not well defined. The lowest occurrence of *M. decussata* was reported by Roth (1978) at a slightly lower level, coinciding with the entry of *Quadrum gartneri*. Sissingh (1977; zone marker) and Verbeek (1977) placed this event considerably higher, in the Upper Coniacian. Roth (1978) recorded the base of *Kamptnerius magnificus* in the Upper Turonian, which is in accordance with my observations.

Coniacian-Santonian

The base of the Coniacian is defined by the lowest occurrence of *Marthasterites furcatus* (Cepek and Hay, 1969a), a definition generally accepted in literature. Manivit et al. (1977) and Sissingh (1977), however, placed the Turonian-Coniacian boundary just below the entry of *M. furcatus*.

The Coniacian-Santonian boundary could not be recognized and no satisfactory subdivision could be made of the Coniacian-lower Santonian. In the wells studied the sidewall core coverage of this interval is inadequate and investigation of selected ditch cuttings helped very little. Relatively little is known about the Coniacian-Santonian boundary interval. In deep-sea cores it is usually represented by a hiatus and the information from land sections is scarce. The subdivisions of the (Upper) Coniacian-Lower Santonian interval proposed by Sissingh (1977) and Verbeek (1977) are both based on only one section (Dyr El Kef, Tunisia). Disagreement exists about the exact locations of the Coniacian and Santonian stratotypes as defined by Coquand (1856, 1858) in the Charente, southern France, but eligible sections in the area are very similar. The stratotypes have been discussed by Séronie-Vivien (1959, 1972) and Van Hinte (1965, 1979). The Coniacian 'type sections' at and around Cognac are barren or contain scarce nannofossils, and probably correspond to the lower or middle Coniacian; the Santonian 'type sections' between Javresac and Saintes are of Late Santonian age (Sissingh, 1977; Verbeek, 1977; Wonders, 1980).

In the Upper Santonian the lowest occurrence of *Rucinolithus hayii* (see Verbeek, 1977) appears to be a useful marker. Within the interval between the entry of *M. furcatus* and the entry of *R. hayii* a number of events occur which, taken separately, are not always reliable markers, but which considered in association with other events are stratigraphically useful.

These events are, in ascending stratigraphic order, are: the lowest occurrence of *Broinsonia furtiva-lacunosa*, the highest occurrence of *Gartnerago striatum*, the lowest occurrences of *Arkhangelskiella specillata*, *Reinhardtites anthophorus* and *Micula concava*. The *Broinsonia furtiva-lacunosa* and the *G. striatum* events probably can be assigned to the Coniacian, the others to the Santonian.

Broinsonia lacunosa, used by Roth (1978) and Verbeek (1977) as an index species whose base coincides with the Coniacian-Santonian boundary could not always be distinguished from *Broinsonia furtiva* in this study. I have therefore placed both forms together in *Broinsonia furtiva-lacunosa*. Its lowest occurrence probably represents the lowest occurrence of the *B. furtiva* form. According to Verbeek (1977) *B. furtiva* first occurred in the Late Coniacian.

Thierstein (1976) considered the exit of *Gartnerago striatum* to be mid-Coniacian, which agrees broadly with my observations. Unfortunately, this species is difficult to recognize when poorly preserved.

The next event, the lowest occurrence of *Arkhangelskiella specillata*, may be the closest to the Coniacian-Santonian boundary, but its usefulness is limited because it is rare at this level. The lowest regular occurrence of *A. specillata* is situated around the entry level (± Upper Santonian) of *Rucinolithus hayii*.

Sissingh (1977) used the entry of *Reinhardtites anthophorus* as a zone marker considering it Early Santonian, which corresponds more or less with the lowest regular occurrence of this species in my material. Forms like *R. anthophorus*, seem to appear earlier, however, between the entry of *Marthasterites furcatus* and the exit of *Gartnerago striatum*.

The position of the next event, the lowest occurrence of *Micula concava* agrees broadly with Roth (1978) and Verbeek (1977), who placed this datum in the middle Santonian. Its usefulness is somewhat restricted, however, by the fact that *M. concava*, especially in the lower part of its range, is not always easy to separate from *Micula decussata*, from which it is supposed to have evolved.

Rucinolithus hayii zone Verbeek 1977 emend.

Definition: The interval from the lowest occurrence of *R. hayii* to the lowest occurrence of *Broinsonia parca*

Age: Late Santonian

Remarks: This interval comprises the *R. hayii* and *Zygodiscus spiralis* Zones of Verbeek (1977). In my opinion *Z. spiralis* is not a useful index species; in my taxonomic concept of this form it has a much longer stratigraphic range than indicated by Verbeek.

The lowest regular occurrences of *Lucianorhabdus cayeuxii* and *Phanulithus obscurus*, and the highest occurrence of *Lithastrinus floralis* occur within this zone. Sissingh (1977) placed the entry of *L. cayeuxii* in the Upper Santonian which agrees well with the position of the lowest regular occurrence of this species in the probabilistic sequence, although rare specimens were found lower, in the interval between the exit of *Gartnerago striatum* and the entry of *Arkhangelskiella specillata*. The lowest regular occurrence of *Phanulithus obscurus* slightly below the entry of *Broinsonia parca* is in accordance with Sissingh (1977), who recorded the entry of *P. obscurus* between the entry of *Lucianorhabdus cayeuxii* and the entry of *B. parca*. But again, scarce specimens of *P. obscurus* were found lower, down to about the entry of *Micula concava*. The exit of *Lithastrinus floralis* is situated just below the entry of *Broinsonia parca*.

Campanian-Maastrichtian

Broinsonia parca Zone Verbeek 1976b

Definition: The interval from the lowest occurrence of *B. parca* to the lowest occurrence of *Ceratolithoides aculeus*

Age: Early Campanian

Remarks: The Santonian-Campanian boundary has been placed at the entry level of *B. parca*, in agreement with Verbeek (1977) and Roth (1978). Sissingh (1977) put this boundary somewhat lower, at the entry level of *Phanulithus obscurus*. Within this zone in ascending stratigraphic order are: the exits of *Marthasterites furcatus*, *Corollithion signum*, and *Podorhabdus coronadventis*. The highest occurrence of *M. furcatus* was used by Sissingh (1977) as a zone marker to subdivide the interval between the entries of *Broinsonia parca* and *Ceratolithoides aculeus*.

Ceratolithoides aculeus Zone Cepek and Hay 1969a, emend. Martini 1976

Definition: The interval from the lowest occurrence of *C. aculeus* to the lowest occurrence of *Quadrum gothicum*

Age: Early-Middle Campanian

Remarks: A stratigraphically useful event within this interval appears to be the highest common occurrence of *Eiffellithus eximius*. Below this level the species is common, whereas above it *E. eximius* occurs rarely and irregularly. The exit of *E. eximius* is in the Lower Maastrichtian (*Arkhangelskiella cymbiformis* Zone).

Quadrum gothicum Zone Martini 1976

Definition: The interval from the lowest occurrence of *Q. gothicum* to the lowest occurrence of *Quadrum trifidum*

Age: Middle-Late Campanian

Remarks: *Quadrum nitidum* of Sissingh (1977) is the same form referred to here as *Q.gothicum*.

Quadrum trifidum Zone Bukry and Bramlette 1970

Definition: The interval from the lowest to the highest occurrence of *Q. trifidum*

Age: Late Campanian-?Early Maastrichtian

Remarks: The Campanian-Maastrichtian boundary is usually placed within this zone, but the chronostratigraphic position of the highest occurrence of *Quadrum trifidum* is somewhat ambiguous. According to Roth (1978) the distribution of *Q. trifidum* was latitudinally controlled. He did not find *Q. trifidum* in lower Maastrichtian sediments at DSDP site 390A (Blake Plateau; paleolatitude 25-30°N, Firstbrook et al., 1979) and stated that in low latitudes this species ranges as high as the entry level of *Lithraphidites quadratus* (i.e. approximately middle Maastrichtian). Martini (1976) on the other hand, reported a gap between the exit of *Q. trifidum* and the entry of *L. quadratus* (gap = *Arkhangelskiella cymbiformis* Zone) at the low latitude sites of DSDP Leg 33 in the central Pacific (paleolatitude 15-30°N, Firstbrook et al., 1979), but Verbeek (1977) did not find firm evidence for such a gap in western Tunisia. Sissingh (1977), however, recorded in the same section in Tunisia the highest occurrence of *Q. trifidum* and below the lowest occurrence of *L. quadratus*.

In the Gulpen Chalk, below the Maastrichtian stratotype (high latitude), *Q. trifidum* is absent (Martini, 1976). Martini suggested that the exit of *Broinsonia parca* can be taken as a substitute for defining the upper boundary of the *Q. trifidum* Zone in high latitudes. At DSDP Leg 33 (central Pacific) he found the highest occurrence of *B. parca* just below the highest occurrence of *Q. trifidum*. Sissingh (1977) placed the exits of *Q. trifidum* and *B. parca* at the same level, just above the Campanian-Maastrichtian boundary.

In the material from the Canadian Atlantic margin I observed a considerable gap between the exit of *Q. trifidum* and the entry of *L. quadratus*. The highest occurrence of *B. parca* is above the highest occurrence of *Q. trifidum*. The exit of *Tranolithus phacelosus*, one of Sissingh's marker events in the Lower Maastrichtian appears to be within the *Q. trifidum* Zone.

If the extinction of *Broinsonia parca* was indeed synchronous, the position of the exit of *Q. trifidum* below the exit of *B. parca* might indicate a suppressed top for *Q. trifidum*, possibly controlled by environmental conditions. Evidence exists for a decrease in paleo-water temperature in the upper part of the *Q. trifidum* Zone (see Paleoecology).

The position of the Campanian-Maastrichtian boundary remains unclear. Some define it by the extinction level of *Eiffellithus eximius* but, as indicated earlier, on the Canadian Atlantic margin the highest occurrence of this species appears to be higher, up to just below the entry of *Lithraphidites quadratus*, undoubtedly in Maastrichtian sediments.

Sissingh's (1977) *Q. trifidum* Zone (defined as the interval from the entry of *Q. trifidum* to the exit of *Reinhardtites anthophorus*) and *Tranolithus phacelosus* Zone (defined as the interval from the exit of *R. anthophorus* to the exit of *T. phacelosus*) both fall within the *Q. trifidum* Zone, recognized on the Canadian Atlantic margin where the highest occurrence of *T. phacelosus* occurs below the exit of *Q. trifidum*.

The highest occurrence of *Reinhardtites anthophorus* is difficult to pinpoint because of transitional forms between *R. anthophorus* and *R. levis*, but it appears to occur just below the highest occurrence of *T. phacelosus* although their relative order in the probabilistic sequence is not well defined.

Arkhangelskiella cymbiformis Zone Perch-Nielsen 1972, emend. Martini 1976

Definition: The interval from the highest occurrence of *Quadrum trifidum* to the lowest occurrence of *Lithraphidites quadratus*

Age: Early-Middle Maastrichtian

Remarks: This zone is equivalent to the *Lithraphidites praequadratus* Zone of Roth (1978), which has the same definition. The exits of *Broinsonia parca* and *Reinhardtites levis* occur within this interval.

The *A. cymbiformis* Zone of Sissingh (1977) is defined as the interval from the highest occurrence of *R. levis* to the lowest occurrence of *Nephrolithus frequens* and corresponds to the upper part of the *A. cymbiformis* Zone as defined here (= *sensu* Martini) and the overlying *Lithraphidites quadratus* zone.

The *Reinhardtites levis* Zone of Sissingh (1977), defined as the interval from the exit of *Tranolithus phacelosus* to the exit of *R. levis*, appears to be equivalent to the upper part of the *Q. trifidum* Zone and the lower part of the *Arkhangelskiella cymbiformis* Zone in this paper.

Lithraphidites quadratus Zone Cepek and Hay 1969a

Definition: The interval from the lowest occurrence of *L. quadratus* to the lowest occurrence of *Nephrolithus frequens*

Age: approximately middle Maastrichtian

Remarks: *Ceratolithoides kamptheri*, a rare, but characteristic form, has its entry within this zone.

Nephrolithus frequens zone Cepek and Hay 1969a

Definition: The interval from the lowest occurrence of *N. frequens* to the highest occurrence of *N. frequens* (and most other Cretaceous species)

Age: Late Maastrichtian

Remarks: The *Micula murus* Zone is the low latitude equivalent of the *N. frequens* zone. Apart from two doubtful specimens, *M. murus* was not found.

Wide sample spacing, barren intervals and hiatuses hamper gaining insight in the processes that took place around the Cretaceous-Tertiary boundary.

The sidewall core coverage at the Cretaceous-Tertiary contact is best in the Adolphus D-50 and Missisauga H-54 wells, where samples are spaced at less than 25 feet. In both wells the *N. frequens* Zone is present. The lowest Tertiary sample in Adolphus D-50 can be assigned to the *Chiasmolithus danicus* Zone (NP3; Late Danian), in Missisauga H-54 to the *Ellipsolithus macellus* Zone (NP4; earliest Thanetian).

QUANTITATIVE BIOSTRATIGRAPHICAL ANALYSIS

Interest in quantitative stratigraphy has been growing in recent years and significant progress has been made in the development of relatively simple statistical methods that can be applied in biostratigraphy. Much of the activity is coordinated in the International Geological Correlation Program (IGCP) Project 148: "Quantitative Stratigraphic Correlation Techniques". The recently formed Canadian Working Group for project 148 aims efforts at the development and application of quantitative biostratigraphic methods to data from exploratory wells in Canadian frontier regions (Agterberg and Gradstein, 1981). A probabilistic model has been developed by Agterberg and Gradstein that has been applied successfully to the Cenozoic foraminiferal stratigraphy of the Labrador Shelf and the northern Grand Banks, where a scarcity of planktonic index species has hampered biostratigraphic correlations (Gradstein and Agterberg, in press). The same statistical model was tested on the Late Cretaceous nannofossil data from the Canadian Atlantic margin. The results are described below and by Doeven et al. (1982).

The Statistical Model

The applied statistical model involves a probabilistic ranking and scaling of biostratigraphic events, operated by the Ranking and Scaling computer program (RASC) developed by F.P. Agterberg and L.D. Nel. The RASC program has essentially three options. The first option is a ranking technique modified from Hay (1972). An optimum (most likely) sequence of events is constructed by paired comparisons of events. The problem of cycling events, a group of events whose relative positions are undetermined, is accounted for in the RASC program. As small samples (numbers of pairs of scores) cause uncertainties in the optimum sequence, it is useful to require that each event occurs in at least k_c sections and each pair of events in at least m_c sections. It is necessary to choose these numbers in such a way that $k_c \geq m_c$; otherwise there might be events in the optimum sequence whose positions are completely undetermined. The relative position of the events in the most likely sequence is an average of all the relative positions encountered. The analyses described in this paper involve mainly this ranking method.

The second option of the RASC program is a scaling of events along a relative time-axis, using the optimum sequence as a starting point. The basic assumption is that the position of an event in a single well or section can be described by means of a normal (Gaussian) probability distribution. From the observed amount of overlap of the probability distributions the distances between the mean values of the probability distributions for successive events are computed. The amount of overlap can be determined from the number of times events change places (so called cross-over frequency). The higher this frequency the closer the events are in time. These inter-event distances are plotted in a dendogram, which represents the clustering of events along a relative time axis. The optimum clusters resemble assemblage zones. The analysis by Gradstein and Agterberg (in press) focusses particularly on this clustering method.

The third option of the RASC program is a normality test. It identifies in each section the events that are out of place compared with the optimum sequence and scores the degree of the anomality.

A comprehensive description of the statistical model is given by Gradstein and Agterberg (in press) and Agterberg and Nel (in press a,b; includes computer algorithms).

The Data Base

The data base for the analyses performed with the RASC computer program comprises the observed sequence of Late Cretaceous nannofossil events in ten exploratory wells: Triumph P-50, Onondaga E-84, Primrose A-41, Missisauga H-54, Mic Mac H-86, Wyandot E-53, Heron H-73, Osprey H-84, Adolphus D-50, and Indian Harbour M-52 (for location see Fig. 1).

In all 119 nannofossil events were selected, representing 64 taxa. Each event was given a unique code number, which was recorded in a dictionary. The input consisted of the observed sequences of (coded) events, accompanied by the dictionary. Simultaneous events were connected by hyphens, which means the computer reads those as occurring in the same sample.

The events consisted of the lowest occurrences, highest occurrences, 'subbottoms' (lowest regular or common occurrences), and 'subtops' (highest regular or common occurrences) of nannofossil species. In a subjective approach

stratigraphically isolated lowest or highest occurrences might be considered due respectively to contamination or reworking and consequently ignored. This data base is not subject to such bias.

The principle of the subtop-subbottom concept is illustrated in Figure 5. This figure shows the stratigraphical distribution of species A and B in wells I and II. In well I species A was consistently found in samples 5 through 8 and occurred isolated in samples 2 and 11. The highest occurrence of species A (code number 98) was in sample 2, the subtop (code no. 298) in sample 5, the subbottom (code no. 398) in sample 8, and the lowest occurence (code no. 198) in sample 11. In well II species A ranged continuously through samples 15 to 20. The highest occurrence and the subtop coincided as did the lowest occurrence and the subbottom. The top of species A was coded 98-298, the base 398-198. In an extreme case where species A occurs in only one sample in a well, all four types of events would coincide and the occurrence would be entered as 98-298-398-198.

WELL I

SAMPLES	SPECIES A			SPECIES B		
	OCCURRENCE	TYPE OF EVENT	CODE NUMBER	OCCURRENCE	TYPE OF EVENT	CODE NUMBER
1						
2	•	HO	98			
3				X	HO	99
4				X		
5	•	ST	298	X		
6	•			XX	ST	299
7	•			XX		
8	•	SB	398	XX		
9				XX		
10				XX	LO	199
11	•	LO	198			
12						

WELL II

SAMPLES	SPECIES A			SPECIES B		
	OCCURRENCE	TYPE OF EVENT	CODE	OCCURRENCE	TYPE OF EVENT	CODE
13				X	HO	99
14				X		
15	•	HO, ST	98-298	X		
16	•			XX	ST	299
17	•			XX		
18	•			XX		
19	•			XX		
20	•	SB, LO	398-198	XX	LO	199
21						
22						

GSC

HO = HIGHEST OCCURRENCE
ST = SUBTOP
SB = SUBBOTTOM
LO = LOWEST OCCURRENCE
X = RARE
XX = COMMON

Figure 5. Example of the subtop-subbottom concept. For an explanation see text.

Table 2: The number of events that occur in at least 1, 2, 3,. . . or all 10 wells, satisfying conditions of minimum occurrence (k_c).

Number of qualifying events	119	117	115	110	106	91	77	68	52	1
$k_c \geqslant$	1	2	3	4	5	6	7	8	9	10

The distribution of species B illustrates the other application of the subbottom-subtop concept. In both wells species B shows a significant change in abundance in the top part of its range. The highest common occurrence of species B (sample 6 in well I and sample 16 in well II) was recorded as a separate event (subtop). Of the 119 entered events 23 are subtops and subbottoms.

Most nannofossil taxa occur in all the wells leading to few missing data. The coherence of the database is illustrated in Table 2, which shows the number of events that occur in at least 1, 2, 3, ... or all 10 wells. Even under the severe condition that an event must occur in 8 of the 10 wells, still more than half of the entered events qualified. The table helps in deciding the minimum number (k_c) of wells in which an event must occur to qualify.

Results

After several runs of the RASC program under varying k_c/m_c conditions the optimum sequence obtained under 3/3 k_c/m_c conditions was chosen as a basis for further evaluation. Out of the 119 entered events 115 qualified, including virtually all marker events used in the previously established conventional (subjective) zonation. Two analyses have been conducted, each with a slightly different data base. In the first one the basic set of data from the ten wells was entered. In the second analysis three of the ten wells – those with the best sample coverage and a relatively good score in the normality test, namely Adolphus D-50, Primrose A-41, and Triumph P-50, were entered twice, increasing the number of wells from 10 to 13. Thus weighting of good records was introduced. A range chart was constructed from the obtained optimum sequences of events.

Figure 6 shows the obtained optimum sequences and ranges; the results of the first analysis (10 wells) are in thick lines, those of the second analysis (13 wells) are in thin lines. The average range of a species is the interval between its lowest and its highest occurrence position as determined in the optimum sequence. The intervals between the lowest occurrence and the subbottom and between the highest occurrence and the subtop of a species are represented by dotted lines. For species with a known entry level below the range of the samples only highest occurrences were used; for most of the species with a known extinction level at the end of he Cretaceous only lowest occurrences were entered. To produce subjectively truncated ranges of these species their lowest or highest occurrence positions in the optimum sequence have been connected with the top or bottom of the chart.

The two highest placed events in the optimum sequence, the highest occurrence of *Arkhangelskiella cymbiformis* (code no. 3) and the highest occurrence of *Nephrolithus frequens* (code No. 58), occur simultaneously. Their ordering in the optimum sequence merely reflects the order in which their code numbers were recorded.

The positions in the optimum sequence of the events used in the subjective zonation are at the horizontal lines dividing the range chart of Figure 6 in successive zonal units. This zonation and the chronostratigraphic interpretations are shown in the left-hand columns of the chart.

The optimum sequence (in both analyses) maintains the order of the marker events as established in the subjective approach. The only anomaly is the highest occurrence of *Podohabdus albianus* (code no. 63). In the subjective zonation the latter, as a subzone marker, was placed above the lowest occurrence of *Quadrum gartneri*. In the optimum sequence the order of these two events is reversed, reflecting the situation in the majority of the studied wells. Between the zone markers in the optimum sequence there are several other events, which are potentially useful for further biostratigraphic refinement. A number of these are incorporated in the biostratigraphic framework, discussed in the previous chapter. The choice of marker events has to be thoughtfully considered, because the positions of closely spaced events may not always be well defined. The dendogram displaying the clustering of events along a relative time axis, one of the options of the RASC program, may serve as a guide in selecting marker events.

The optimum sequence of the second analysis, in which data from the Adolphus D-50, Primrose A-41, and Triumph P-50 wells were entered twice, compares favourably to the optimum sequence of the first analysis. There is some minor reshuffling of positions, mainly in the Cenomanian and Lower Maastrichtian intervals. As to the zone markers, the lowest occurrence of *Ceratolithoides aculeus* has dropped some places in the sequence and the lowest occurrence of *Quadrum gothicum* is situated some positions higher. An improvement is that the highest occurrence of *Watznaueria britannica*, used to delineate the Albian-Cenomanian boundary, now satisfies the imposed 3/3 k_c/m_c conditions.

One of the most detailed zonations of the Upper Cretaceous is by Sissingh (1977). In the conventional approach a number of Sissingh's index species did not seem to be useful. Some of these species could not be consistently identified (owing to poor preservation or to morphological transition to other species), others showed irregular occurrences that did not conform to Sissingh's scheme. Surprisingly, Sissingh's zonation is almost exactly duplicated in the optimum sequence, if the subtop-subbottom concept is utilized. The right-hand column of Figure 6 shows Sissingh's Upper Cretaceous marker events, which are numbered stratigraphically downward from 1 to 19. With the exception of no. 14, these events are positioned in the same order in the optimum sequence. The anomalous position of event 14, the lowest occurrence of *Micula* ex gr. *staurophora* (in which Sissingh included *M. decussata* and *M. concava*) may be due

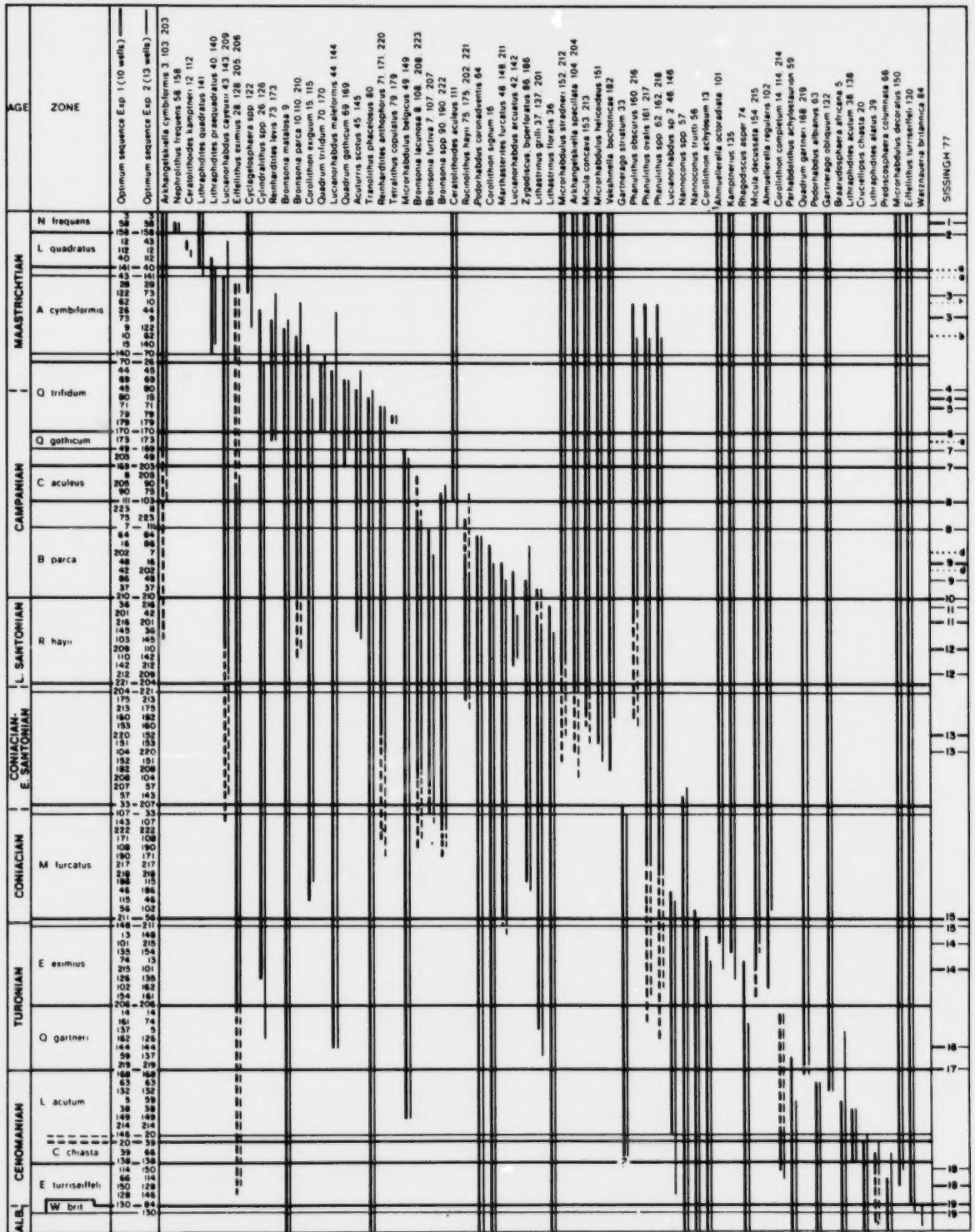

Figure 6. Probabilistic nannofossil range chart. For an explanation see text.

to a different concept of this species but also the frequency of occurrence may be a factor. On the Canadian Atlantic margin *M. decussata* usually occurs in low numbers in the Turonian and becomes more frequent in the Coniacian (a distinct subbottom, however, could not be recognized). Sissingh put its lowest occurrence in the Upper Coniacian. The only other deviations are two of Sissingh's subzone markers, the highest occurrence of *Broinsonia parca* (b) and the lowest occurrence of *Reinhardtites levis* (c). In Sissingh's scheme event b is situated between events 4 and 5 (in the optimum sequence between 3 and 4) and event c between 5 and 6 (in the optimum sequence between 6 and 7). The base of *R. levis* (c) is difficult to pinpoint, because it appears to have evolved gradually from *R. anthophorus* (Sissingh, 1977).

Analyzing the ranges of some species with regard to the subtop-subbottom concept, one faces a number of different situations. In some cases the subbottom and lowest occurrence events have adjacent positions in the optimum sequence (e.g. *Marthasterites furcatus*, code no. 211, 148, and *Quadrum gartneri*, code no. 219, 168). Here the (rare) 'anomalous' lowest occurrences in some wells (presumably due to drilling mud contamination) do not affect the relative position of the event and the use of subbottoms appears not to have been meaningful.

In other cases, however, there is a substantial difference in position between the subtops/subbottoms and the corresponding highest/lowest occurrences. Irregular and relatively rare occurrences below or above the regular or common range of a species may be attributed to drilling mud contamination or reworking, but other factors can also be involved. For example, *Eiffellithus eximius* has been found only sporadically above the middle Campanian; its (average) highest occurrence level is near the middle Maastrichtian. In literature the extinction datum of *E. eximius* is often placed at the end of the Campanian. Perhaps the observed decrease in abundance of *E. eximius* in the Upper Campanian resulted from a slow extinction process, accelerated by climatic deterioration in Late Campanian-Maastrichtian time (see Paleoecology). In any case, the subtop of *E. eximius* (code no. 205) seems to be a consistent and useful marker on the Canadian Atlantic margin and is more reliable than the highest occurrence event (code no. 28).

The position of the lowest occurrence of *E. eximius* considerably below the subbottom presumably is due in part to some contaminated samples, but on the other hand its supposed evolution from *E. turriseiffeli* (Verbeek, 1977) may be a factor. Transitional types do occur and an overall '*E. turriseiffeli*-population' may contain rare early forms of the '*E. eximius*-type'. The lowest regular occurrence (subbottom) of *E. eximius* usually can be readily located, and its stratigraphic position agrees with the position of the entry of *E. eximius* as reported by Manivit *et al.* (1977) and Verbeek (1977).

Corollithion completum also has a substantial interval between its highest occurrence (code no. 14) and its subtop (code no. 214). The position of its highest occurrence in the optimal sequence (high up in the Turonian) is deceptive, because it is recorded only in the Upper Cenomanian-lowest Turonian interval (coinciding with the subtop), or,in a few wells, as isolated occurrences in the Upper Campanian and Maastrichtian. The resulting average top just below the subbottom of *E. eximius* is meaningless, while the (average) subtop of this distinctive species in the Upper Cenomanian has some biostratigraphic value. *C. completum* has seldom been reported in literature. It has been regularly recorded in the Cenomanian-lowest Turonian interval of the El Kef section in Tunisia (Verbeek, 1977) and isolated occurrences are known in the Upper Campanian in southern Spain (Verbeek, 1977) and Maastrichtian on Madagascar (Perch-Nielsen, 1973; original description). In view of this stratigraphic distribution, reworking may not be satisfactory to explain the disjunct stratigraphic range of *C. completum* on the Canadian Atlantic margin.

Lucianorhabdus cayeuxii, *Phanulithus obscurus*, *P. ovalis*, and nannoconids are usually considered indicative of nearshore environments and their occurrences influenced by environmental factors. Nevertheless, the tops and bottoms of their regular occurrences (subtops and subbottoms) can be regionally useful markers.

The application of the RASC quantitative stratigraphic method to the Cretaceous nannofossil record of the Canadian Atlantic margin results in a zonation that closely matches the most detailed subjective zonation. It provides readily available guidelines for further biostratigraphic refinement. The subtop-subbottom concept, where applicable, gives a better insight into the stratigraphic distribution of a species than the mere use of lowest and highest occurrences. In many cases subtop and subbottom events are more reliable markers than the highest or lowest occurrences of species.

COMPARISON WITH OTHER MICROFOSSIL ZONATIONS

Extensive biostratigraphical data on the foraminifers, dinoflagellates and spores from exploratory wells on the Atlantic continental margin have been gathered by the Geological Survey of Canada in Dartmouth, Nova Scotia. Publications include Ascoli, 1976; Barss et al., 1979; Bujak and Williams, 1977, 1978; Gradstein, 1976, 1978; Gradstein and Agterberg, in press; Gradstein and Berggren, 1981; Gradstein and Srivastava, 1980; Gradstein and Williams, 1976; Gradstein et al., 1975; Jansa et al., 1980; Williams, 1975; Williams and Brideaux, 1975; Williams and Bujak, 1977. The data potentially afford the opportunity of effecting a first order correlation between the foraminiferal, palynological, and nannofossil biostratigraphies of this region. A detailed correlation of biodatums is seriously hampered, however, by the quality of the samples and by the fact that different biostratigraphic methods have been used.

The material available for the palynological and foraminiferal analyses generally consisted of 30 foot composite cuttings samples taken at 100 foot intervals, complemented by relatively few sidewall core and isolated conventional core samples. In the present nannofossil study sidewall core samples have mainly been used, supplemented by cuttings and conventional core samples. By processing of individual cuttings fragments and examining their nannofossil content the effects of caving in the nannofossil analysis have been reduced. The 100 foot spacing of the cuttings samples and the irregular distances between the sidewall cores introduce another element of inaccuracy in the correlations.

Because of the nature of the samples and the methods used to examine them the palynological and foraminiferal

biostratigraphy is based solely on highest occurrences (tops, exits) of taxa, whereas the present nannofossil study results in a more refined biostratigraphy, employing both lowest and highest occurrences of taxa. A highest occurrence has the disadvantage that it may have been extended upward by reworking.

The nannofossil zones proposed here are interval zones, delineated by two biohorizons (lowest and highest occurrences of species). The palynological and foraminiferal zones, however, were defined by the highest occurrences of a number of diagnostic species within the zoned interval. These zones were stated by Barss et al. (1979, palynomorphs) and Ascoli (1976, foraminifera) to be assemblage zones "in accordance with the American Commission on Stratigraphic Nomenclature (1961, art. 21)". In my view, however, these zones would be better termed interval zones, because essentially the zonal boundries are defined by biodatum horizons (tops).

A first order correlation of the nannofossil stratigraphy with the palynological and foraminiferal stratigraphies in a number of wells is shown in Figures 8-13 and 15-17. Because the palynological and most of the foraminiferal data do not indicate the precise footages for the diagnostic species tops, a close correlation of biodatum horizons is not possible. A comparison of the three microfossil stratigraphies therefore must be largely restricted to a comparison of the respective chronostratigraphical interpretations. If more detailed palynological and foraminiferal data become available, a future study, preferably conducted on a quantitative basis, could result in the establishment of a sophisticated integrated microfossil stratigraphy for the Canadian Atlantic margin.

Dinoflagellate-Spore Zonations

The Albian-Maastrichtian part of Barss et al.'s (1979) regional palynological zonation, which is a modified version of Williams' (1975) zonation, is outlined in Figure 7. It has seven zones, each zone corresponding exactly to a stage. All zones but one are interval (assemblage) zones, defined by the highest occurrences of diagnostic palynomorph species (in majority dinoflagellates). The *Surculosphaeridium longifurcatum* Zone (Turonian) is a peak (acme) zone.

The dinoflagellate-spore and nannofossil stratigraphies are compared using data from the following wells: Mississauga H-54 (Fig. 8), Mohawk B-93 (Fig. 9), Primrose A-41 (Fig. 10), Triumph P-50 (Fig. 11), Wyandot E-53 (Fig. 12), all located on the Scotian Shelf, and Indian Harbour M-52 (Fig. 13) situated on the Labrador Shelf. No palynological data are available for the Adolphus D-50 well (northern Grand Banks), which, from the nannofossil analysis, appears to have the most complete stratigraphic succession. The palynological zones and the diagnostic species for each zone (Barss et al., 1979; Williams, personal communication, 1980) are given for each well.

The figures show a considerable variation in the diagnostic species for each of the zones. The *Cleistosphaeridium polypes* Zone (Cenomanian) and the *Odontochitina operculata* Zone (Campanian) generally have the greatest number of diagnostic species, which in most cases include the denominating species. These zones are apparently the best defined ones (most consistent). The *Oligosphaeridium pulcherrimum* Zone (Coniacian), the *Cordosphaeridium truncigerum* Zone (Santonian), and the *Dinogymnium euclaensis* Zone (Maastrichtian) show the greatest variety of diagnostic species used and in nearly all cases the denominating species are not recorded. Recognition of the *Surculosphaeridium longifurcatum* Peak Zone in most of those wells is based on the abundance of *S. longifurcatum*.

Albian nannofossil assemblages have been found only in Triumph P-50 (Fig. 11) of the wells considered here. In it, the lower part of the *Eiffellithus turriseiffeli* Zone (Upper Albian), characterized by the occurrence together of *E. turriseiffeli* and *Watznaueria britannica*, corresponds to the upper part of the *Spinidinium* cf. *S. vestitum-Eucommiidites minor* Zone (Albian).

'AGE'	SCOTIAN SHELF AND GRAND BANKS ZONE OR SUBZONE	LABRADOR SHELF
MAASTRICHTIAN	Dinogymnium euclaensis	Amphidiadema nucula -Hexagonifera chlamydata assemblage
CAMPANIAN	Odontochitina operculata	
SANTONIAN	Cordosphaeridium truncigerum	
CONIACIAN	Oligosphaeridium pulcherrimum	
TURONIAN	Surculosphaeridium longifurcatum (PEAK)	
CENOMANIAN	Cleistosphaeridium polypes	
ALBIAN	Spinidinium cf. S. vestitum -Eucommiidites minor Rugubivesiculites rugosus	

Figure 7. Palynomorph zonation for the Albian-Maastrichtian rocks of the Canadian Atlantic margin (after Barss et al., 1979).

The top of the *Cleistosphaeridium polypes* Zone (Cenomanian), supposedly one of the best defined zones, is situated in the upper part of the *Lithraphidites accutum* zone (Upper Cenomanian), between the highest occurrence of *Cruciellipsis chiastia* and the lowest occurrence of *Gartnerago obliquum* in Missisauga H-54 (Fig. 8), Triumph P-50 (Fig. 11), and Wyandot E-53 (Fig. 12). In Primrose A-41 (Fig. 10) the top of the *C. polypes* Zone is lower, considerably below the highest occurrence of *C. chiastia*. There is, however, a thick interval with no palynological information in this well. In the nannofossil analysis there appeared to be a hiatus in Primrose A-41, between 5120 and 5120.5 feet (conventional core), accounting for the top part of the *Lithraphidites acutum* Zone, the *Quadrum gartneri* Zone, and the *Eiffellithus eximius* Zone, which cover the uppermost Cenomanian and the Turonian. Such a hiatus was not recognized in the palynological analysis. Approximately at the level of the disconformity a palynomorph assemblage with *Cicatricosisporites hughesi* has been assigned to the Cenomanian-Turonian.

The top of the *Surculosphaeridium longifurcatum* Peak Zone (Turonian) occurs at the same level as the lowest occurrence of *Marthasterites furcatus* (base Coniacian) in Missisauga H-54 (Fig. 8), but slightly lower in Wyandot E-53 (Fig. 12; between the lowest occurrence of *Eiffellithus eximius* and the lowest occurrence of *M. furcatus*) and substantially lower in the Triumph P-50 well (Fig. 11; below the lowest occurrence of *E. eximius*). In all three cases, however, there is a fairly thick interval with no palynological data.

The correlation of the *Oligosphaeridium pulcherrimum* Zone (Coniacian) and the *Cordosphaeridium truncigerum* Zone (Santonian) with the nannofossil scheme is difficult. The *O. pulcherrimum* and *C. truncigerum* Zones seem not particularly well defined in the wells considered here and the position of the Coniacian-Santonian boundary is a problem in the nannofossil stratigraphy.

The *Oligosphaeridium pulcherrimum* Zone (Coniacian) corresponds broadly to the Coniacian-lower Santonian nannofossil interval in Missisauga H-54 (Fig. 8), Primrose A-41 (Fig. 10), and Wyandot E-53 (Fig. 12). The top of

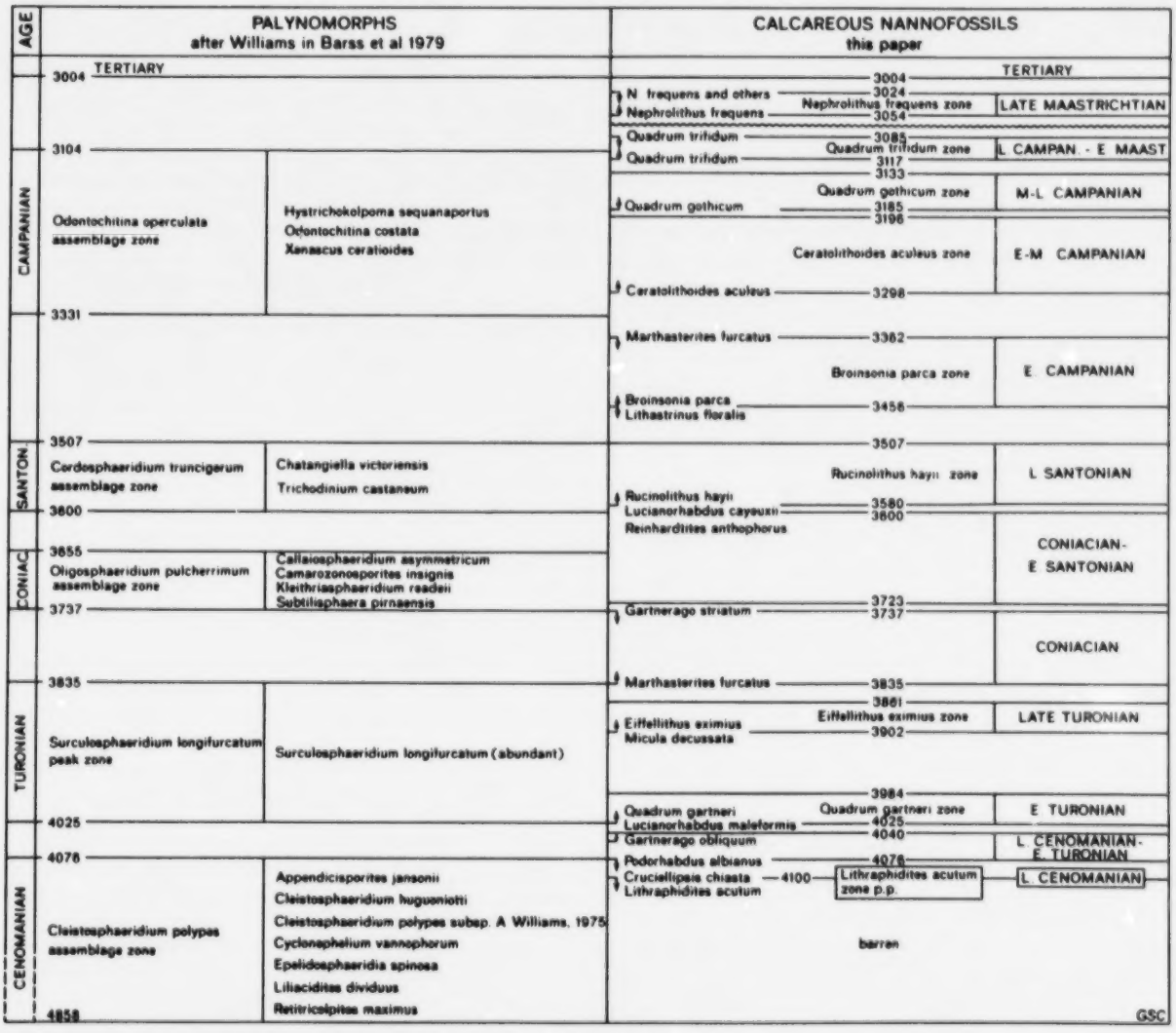

Figure 8. Correlation between the Upper Cretaceous palynomorph and nannofossil stratigraphies in the Missisauga H-54 well on Scotian Shelf.

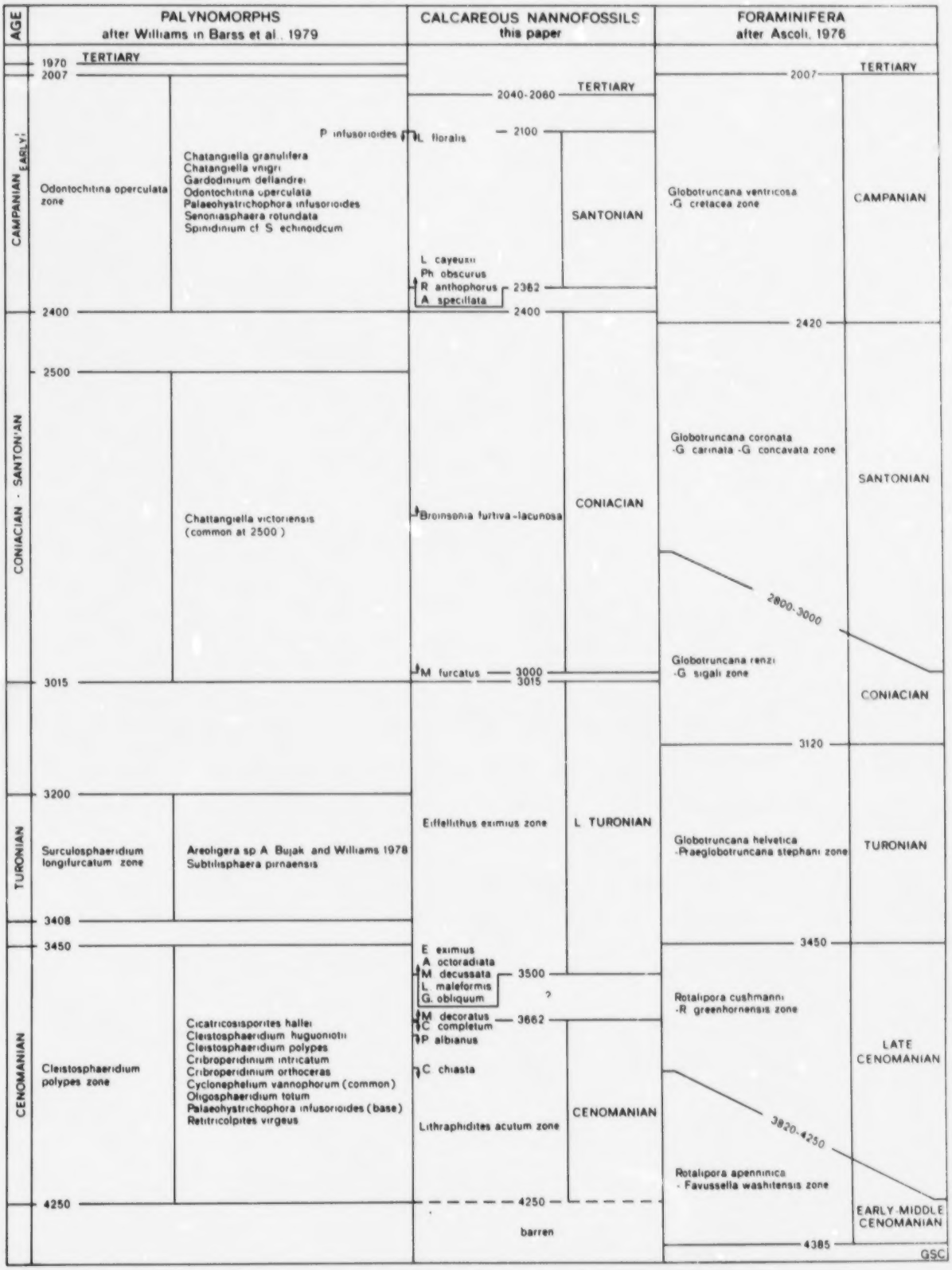

Figure 9. Correlation between the Upper Cretaceous palynomorph, nannofossil, and foraminiferal stratigraphies in the Mohawk B-93 well on Scotian Shelf.

this zone is situated in Primrose A-41 just below the lowest occurrence of *Rucinolithus hayii* (Upper Santonian), but in Wyandot E-53 far below this horizon. On the basis of nannofossils a hiatus is assumed in the Triumph P-50 well (Fig. 11; between 6045 and 5980 feet), representing the Coniacian and lower Santonian. There is no palynological evidence for such a hiatus. A palynologically designated undifferentiated Coniacian- Santonian interval, which contains amongst others the highest occurrence of the Santonian index species *Cordosphaeridium truncigerum*, corresponds in Triumph P-50 to the *Rucinolithus hayii* Zone (Upper Santonian) and the *Broinsonia parca* Zone (lower Campanian) and should in view of the nannofossil data rather be assigned to the Santonian than to the Coniacian.

The *Cordosphaeridium truncigerum* Zone (Santonian) correlates in Missisauga H-54 (Fig. 8) with the *Rucinolithus hayii* zone (Upper Santonian) and in Primrose A-41 (Fig. 10) with the *R. hayii* Zone and at least the *Broinsonia parca* Zone (Upper Santonian-Lower Campanian). In the Wyandot E-53 well (Fig. 12) the rather ill-defined *C. truncigerum* Zone corresponds to part of the interval assigned to the Coniacian-?Lower Santonian in the nannofossil analysis. There might be a hiatus representing part of the Santonian in this well (between 1369 and 1360 feet).

The top of the *Odontochitina operculata* Zone (Campanian), supposedly one of the best defined zones, falls within the *Quadrum trifidum* Zone (Upper Campanian-Lower Maastrichtian) in Missisauga H-54 (Fig. 8), Primrose A-41 (Fig. 10), and Wyandot E-53 (Fig. 12). In Triumph P-50 this top is just below the lowest occurrence of *Quadrum trifidum*, but there are no palynological data from the interval corresponding to the *Q. trifidum* Zone.

The lower boundary of the *O. operculata* Zone is more variable, as should be expected in this type of zonation, where the lower boundary of a zone is defined by the highest occurrence of species delineating the top of the underlying zone (in this case the supposedly less well defined *C. truncigerum* Zone). In Missisauga H-54 (Fig. 8), Primrose A-41 (Fig. 10), and Triumph P-50 (Fig. 11) the base of the *O. operculata* Zone falls roughly within the Lower-Middle Campanian interval of the nannofossil stratigraphy; in Triumph P-50 it is situated as high as the lowest occurrence of *Quadrum gothicum*. In Wyandot E-53, on the other hand, the lower boundary of this zone is positioned below the lowest occurrence of *Rucinolithus hayii* (Upper Santonian).

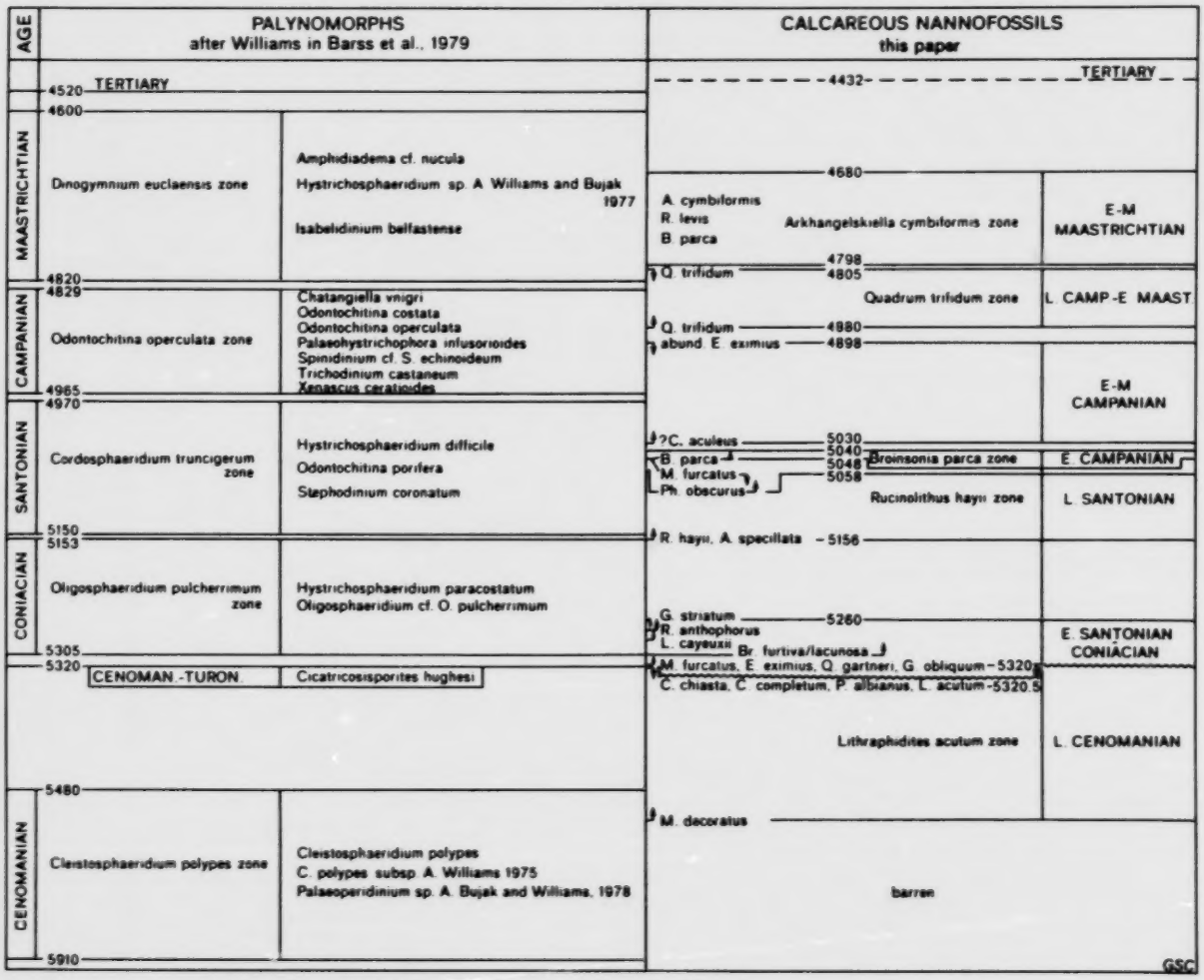

Figure 10. Correlation between the Upper Cretaceous palynomorph and nannofossil stratigraphies in the Primrose A-41 well on Scotian Shelf.

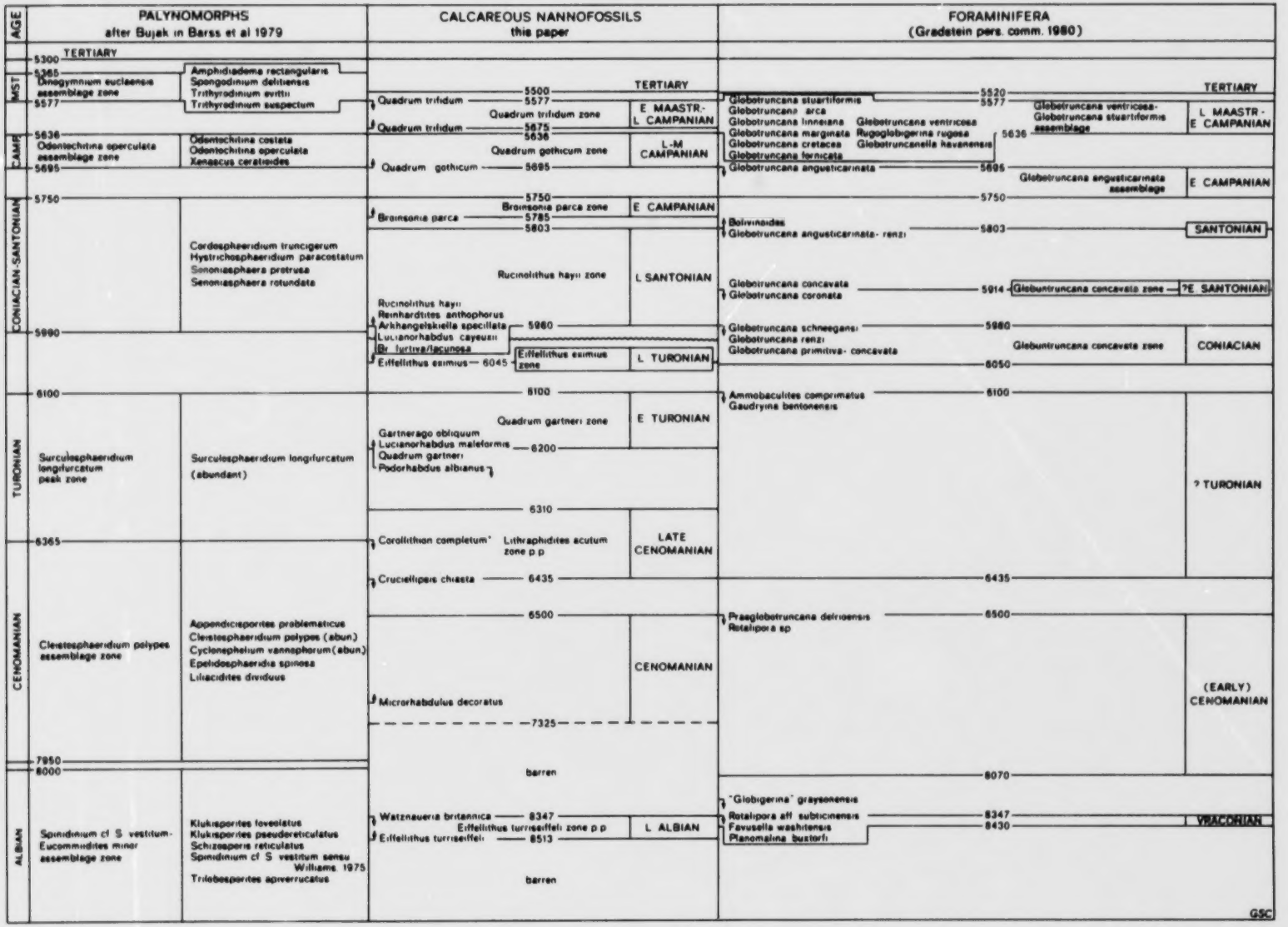

Figure 11. Correlation between the Albian-Maastrichtian palynomorph, nannofossil, and foraminiferal stratigraphies in the Triumph P-50 well on Scotian Shelf.

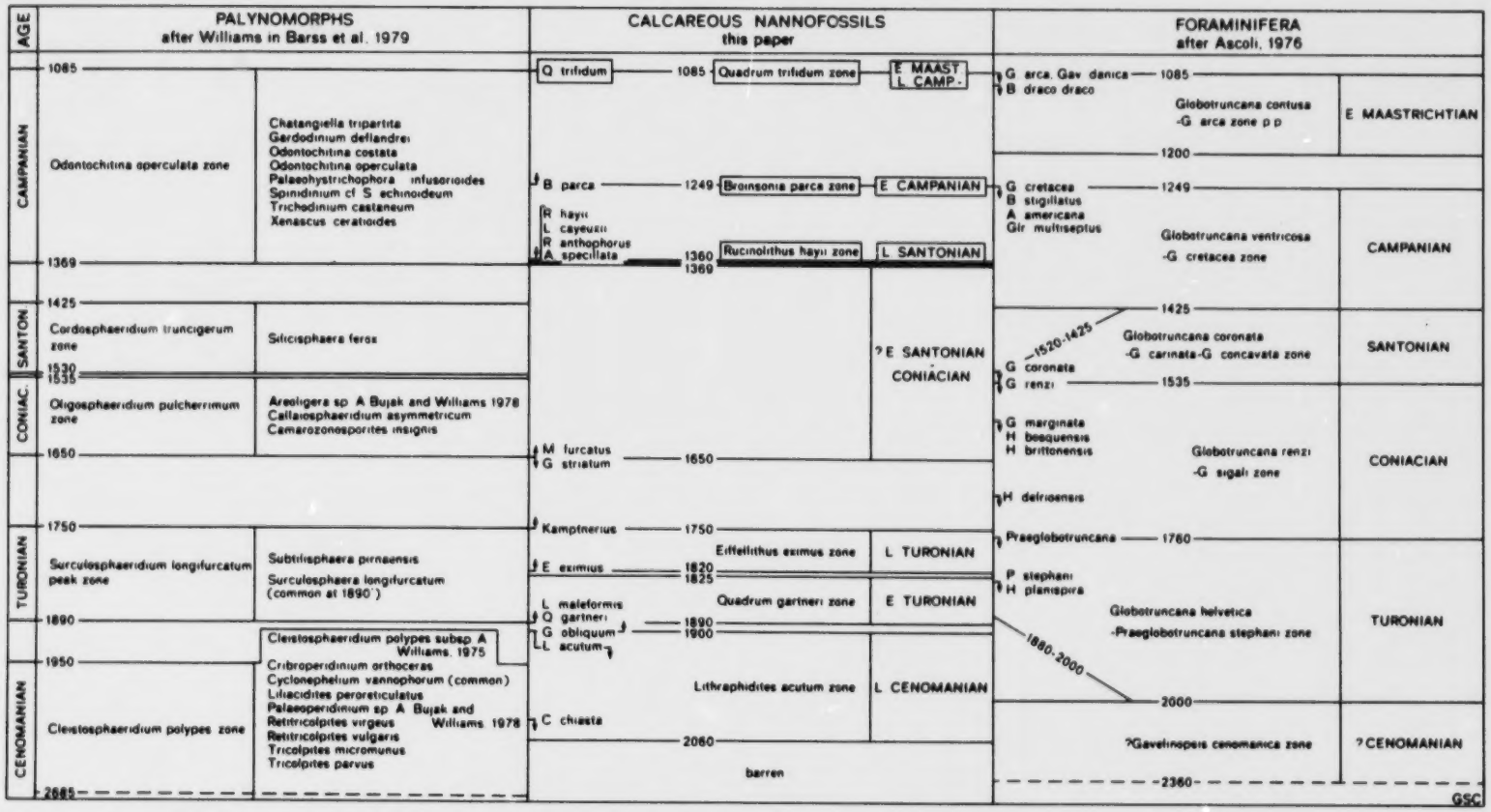

Figure 12. Correlation between the Upper Cretaceous palynomorph, nannofossil, and foraminiferal stratigraphies in the Wyandot E-53 well on Scotian Shelf.

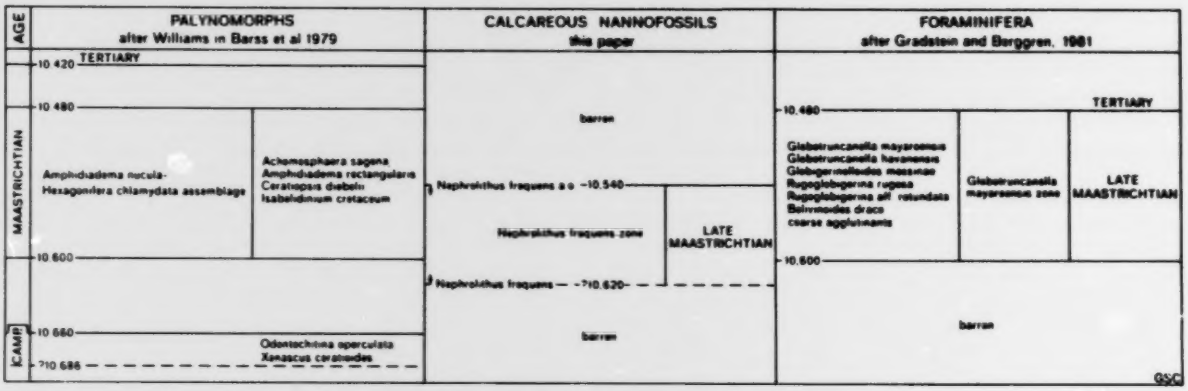

Figure 13. Correlation between the Upper Cretaceous palynomorph, nannofossil and foraminiferal stratigraphies in the Indian Harbour M-52 well on Labrador Shelf.

The '*Amphidiadema nucula - Hexagonifera chlamydata* assemblage' (Maastrichtian) in Indian Harbour M-52 (Fig. 13), which incidentally does not contain the denominating species, corresponds more or less to the Upper Maastrichtian *Nephrolithus frequens* Zone. In Primrose A-41 (Fig. 10) the Maastrichtian *Dinogymnium euclaensis* Zone is partly equivalent to the *Arkhangelskiella cymbiformis* Zone (Lower-Middle Maastrichtian). The *D. euclaensis* Zone in Triumph P-50 (Fig. 11) covers an interval that in the nannofossil and foraminiferal analyses is assigned to the Tertiary. I am inclined to think that the Maastrichtian dinoflagellates in this interval are reworked. The thin slice of Upper Maastrichtian sediments (*Nephrolithus frequens* Zone)in the Missisauga H-54 well was not recognized in the palynological analysis.

The chronostratigraphic interpretations in the Mohawk B-93 well (Fig. 9) show some unexplainable discrepancies. The *Cleistosphaeridium polypes* Zone (Cenomanian) partly overlaps the nannofossil Cenomanian interval, but the top of the zone is situated above the lowest occurrence of *Eiffellithus eximius* (Upper Turonian). The *Surculosphaeridium longifurcatum* Peak Zone (Turonian) (without the primary index species *S. longifurcatum*) falls within the thick interval assigned to the *E. eximius* zone (Upper Turonian). A palynologically undifferentiated ill-defined Coniacian-Santonian interval matches largely an interval assigned to the Coniacian on the basis of nannofossils. The *Odontochitina operculata* Zone (Campanian) in Mohawk B-93 is for the most part equivalent to an interval with typical Santonian nannofossil assemblages.

Foraminiferal Zonations

The foraminiferal data employed to correlate the foraminiferal stratigraphy with the nannofossil stratigraphy have been taken from Ascoli (1976), Gradstein (personal communication 1980), and Gradstein and Berggren (1981). The different ways in which these data were presented make the correlationrather complicated.

Ascoli (1976) provided an eight fold subdivision of the Albian-Maastrichtian succession on the Scotian Shelf and southwestern Grand Banks using planktonic foraminifera, and presented alternative zonations based on calcareous benthonic and arenaceous benthonic foraminifera (Fig. 14). In general, each of Ascoli's zones represents a stage. Each is defined by a number of highest occurrences within the zoned interval. The foraminiferal stratigraphy of the Mic Mac H-86 (Fig. 15), Mohawk B-93 (Fig. 9), Onondaga E-84 (Fig. 16), and Wyandot E-53 wells (Fig. 12) is after Ascoli (1976). Ascoli gave zonal assignments and chronostratigraphic interpretations, but no information about the actual diagnostic species upon which these assignments were based.

The foraminiferal data for Adolphus D-50 (Fig. 17), Triumph P-50 (Fig. 11), and Indian Harbour M-52 (Fig. 13) are from Gradstein (personalcommunication 1980) and Gradstein and Berggren (1981). For the Triumph P-50 and Indian Harbour M-52 wells the highest occurrences of stratigraphically important species, and chronostratigraphical interpretations based on them are given. The regional zonal scheme of Ascoli is not followed. Good sidewall core coverage in Adolphus D-50 permitted the use of lowest occurrences of foraminiferal species and reference to be made to the standard planktonic foraminifera zonation of Van Hinte (1976). The correlation of the present nannofossil stratigraphy with some of Van Hinte's zones can be compared with the nannoplankton-planktonic foraminifera correlation schemes of Sissingh (1978) and Wonders (1980).

Sissingh (1978) compared his nannofossil zonation (Sissingh, 1977; Fig. 4) with the planktonic foraminiferal zonations of Van Hinte (1976), Postuma (1971), and Moullade (1966) based on sections in northeastern France and Tunisia (Dyr El Kef). Wonders (1980) provided a first-order correlation between his planktonic foraminiferal zonation and the nannofossil zonation of Verbeek (1977; Fig. 4) based on the El Burrueco section in southern Spain and the Dyr El Kef section in Tunisia. Wonders also compared his zonation with several other planktonic foraminiferal zonations, among them that of Van Hinte (1976).

The oldest recognized nannofossil zone, the *Prediscosphaera columnata* Zone (middle Albian) was encountered only in the Adolphus D-50 well (Fig. 17). The upper part of the *P. columnata* Zone corresponds to an interval assigned to the Upper Albian *Ticinella breggiensis* Zone of Van Hinte (LC 17). The *T. breggiensis* Zone may reach into

AGE		PLANKTONIC FORAMINIFERA ZONE	DIAGNOSTIC PLANKTONIC SPECIES	DIAGNOSTIC BENTHONIC SPECIES	CALCAREOUS BENTHONIC FORAMINIFERA ZONE	ARENACEOUS BENTHONIC FORAMINIFERA ZONE
MAASTRICHTIAN		Globotruncana contusa Globotruncana arca*	Globotruncana contusa Globotruncana arca* Globotruncana conica Globotruncana ?elevata* Globotruncana fornicata* Globotruncana gansseri Globotruncana rosetta* Globotruncana stuarti Globotruncana stuartiformis* Globotruncanella havanensis Guembelina cretacea Heterohelix navarroensis Pseudotextulana elegans Rugoglobigerina rotundata	Bolivina incrassata gigantea Bolivinoides draco miliani* Bolivinoides draco draco Bolivinoides draco miliani* Bolivinoides laevigatus* Epistomina supracretacea Gavelinella gr. clementiana* Gravelinella taylorensis* Stensioina pommerana Tritaxia spp	Bolivina incrassata gigantea Globorotalites michelianus	Tritaxia spp
CAMPANIAN		Globotruncana ventricosa Globotruncana calcarata*	Globotruncana ventricosa Globotruncana calcarata* Globotruncana angusticarinata Globotruncana elevata Globotruncana hilli Globotruncana lapparenti Globotruncana linneiana Globotruncana marginata*	Neoflabellina numismalis Neoflabellina rugosa leptodisca* Arenobulimina americana* Bolivinoides decoratus decoratus Bolivinoides stingellatus* Epistomina lavosoides Gavelinella pertusa Kyphopyxa christneri* Neoflabellina deltoidea* Stensioina exsculpta Stensioina exsculpta gacilis* Stensioina labyrinthica	Neoflabellina numismalis Neoflabellina rugosa leptodisca	Arenobulimina americana
SANTONIAN		Globotruncana coronata Globotruncana carinata Globotruncana concavata*	Globotruncana coronata Globotruncana carinata Globotruncana concavata* Hedbergella bosquensis	Globorotalites multiseptus Bulimina sp. 3 Epistomina stelligera alveolata Gavelinella sculptilis Neoflabellina praerugosa* Neoflabell. sphaenoid. praecursor Planulana lebusi	Globorotalites multiseptus	
CONIACIAN		Globotruncana renzi Globotruncana sigali	Globotruncana renzi Globotruncana sigali Globotruncana imbricata Globotruncana primitiva Globotruncana schneegansi Hedbergella amabilis Hedbergella brittonensis Hedbergella delrioensis	Epistomina stelligera stelligera Haplophragmoides spp. Marssonella trochus Trochammina spp. Trochammoides spp.	Epistomina stelligera stelligera	"Mesozoic coarse arenaceous Foraminifera" Marssonella trochus
TURONIAN		Globotruncana helvetica Praeglobotruncana stephani	Globotruncana helvetica Praeglobotruncana stephani Clavihedbergella simplex Globigerinelloides caseyi* Hedbergella planispira Praeglobotruncana difformis Praeglobotruncana turbinata*	Gavelinopsis tourainensis Lingulogavelinella turonica* Ammobaculites comprimatus* Dorothia aff. filiformis* Gavelinella baltica Gavelinopsis cenomanica* Lingulogav. asterigerinoides*	Gavelinopsis tourainensis Lingulogavelinella turonica	
CENOMANIAN	LATE	Rotalipora cushmani Rotalipora greenhornensis*	Rotalipora cushmani Rotalipora greenhornensis* Globigerinelloides bentonensis Praeglobotruncana delrioensis	Gavelinopsis cenomanica Ammobaculites comprimatus Dorothia aff. filiformis Haplophragmoides sp. 1 Gaudryina sp. 1 Lingulogavelinella turonica Spiroplectammina sp. 1	Gavelinopsis cenomanica	Dorothia aff. filiformis Ammobaculites comprimatus
	E-M	Rotalipora appenninica Favusella washitensis*	Rotalipora appenninica Favusella washitensis* Rotalipora ticinense*	Gavelinella intermedia Gavelinopsis berthelini Gavelinella ammonoides Patellina subcretacea	Gavelinella intermedia Gavelinopsis berthelini	
ALBIAN		Ticinella praeticinensis Ticinella primula	Ticinella praeticinensis Ticinella primula Ticinella breggiensis Ticinella gaultina Ticinella roberti Globigerinelloides ferreolensis Planomalina buxtorfi	Epistomina carpenteri* Epistomina cretosa* Epistomina chapmani Lenticulina gaultina Gavelinella intermedia Gavelinopsis berthelini Haplophragm gr. topagorukensis Pseudonubeculina nodulosa* Reophax minuta	Lenticulina gaultina Epistomina chapmanni	Haplophragmoides gr. topagorukensis Pseudonubeculina nodulosa
					Epistomina cretosa Epistomina carpenteri	

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Figure 14. Albian-Maastrichtian foraminiferal zonations for the Scotian Shelf and southern Grand Banks (after Ascoli, 1976). Species marked with an asterisk (*) have their stratigraphic highest occurrence within the lower part of the zone.

the *Eiffellithus turriseiffeli* Zone, but this has not been ascertained because of the wide spacing of the foraminifera samples. This correlation agrees well with Sissingh (1978) and Wonders (1980). Sissingh placed the *T. breggiensis* Zone around the lowest occurrence level of *E. turriseiffeli* (= base *E. turriseiffeli* Zone). The *Pseudothalmanninella subticinensis* Zone of Wonders, which corresponds to the middle part of the *T. breggiensis* Zone of Van Hinte, is correlative with the upper part of the *P. columnata* Zone.

The *Planomalina buxtorfi-Rotalipora ticinensis* Zone (LC18) was recognized in Adolphus D-50 (Fig.17) in an interval assigned to the lower part of the *Eiffellithus turriseiffeli* Zone, just below the highest occurrence of *Watznaueria britannica* (considered to mark the Albian-Cenomanian boundary). Sissingh (1978) also placed the *P. buxtorfi-R. ticinensis* Zone in the lower part of the *E. turriseiffeli* Zone around the Albian-Cenomanian boundary. The *Pseudothalmanninella ticinensis-Planomalina buxtorfi* Zone of Wonders (1980), although not quite equivalent to Van Hinte's *P. buxtorfi-R. ticinensis* Zone (a slightly differently defined upper boundary), has been correlated with the lower part of the *E. turriseiffeli* Zone as well. A similar foraminiferal assemblage (with *P. buxtorfi*) in Triumph P-50 (Fig. 11) occurs in the same position with respect to the nannofossil scheme.

A foraminiferal assemblage with *Rotalipora appenninica* and *Praeglobotruncana delrioensis*, assigned to the *Rotalipora reicheli-R. gandolfii-R. greenhornensis* Zones of Van Hinte (UC1-2), falls in Adolphus D-50 (Fig. 17) within the upper part of the *E. turriseiffeli* Zone (Lower Cenomanian), between the highest occurrence of *W. britannica* and the lowest occurrence of *Lithraphidites acutum*. In Triumph P-50 (Fig. 11) the highest occurrence of *P. delrioensis* is situated approximately in the middle Cenomanian between the lowest occurrence of *Microrhabdulus decoratus* and the highest occurrence of *Cruciellipsis chiastia*. The lowest occurrence of *L. acutum* could not be determined in Triumph P-50.

Sissingh (1978) correlated Van Hinte's first three Upper Cretaceous zones (UC1-3; *R. gandolfii/R. greenhornensis* to *R. cushmanni* Zone) with the upper part of his *E. turriseiffeli* Zone and most of his *M. decoratus* Zone, which together span almost the whole Cenomanian. In Adolphus D-50 the lowest occurrence of *M. decoratus* (which marks the base of Sissingh's *M. decoratus* Zone) is situated at the top of the interval assigned to UC1-2. Wonders (1980) equated the interval covered by Van Hinte's UC1 and UC2 with his *Thalmaninella apenninica* Zone and his *T. globotruncanoides* Zone, which correspond to the upper part of the *E. turriseiffeli* zone and the lower part of the *L. acutum* zone (approximately Lower-middle Cenomanian).

The upper part of the *Rotalipora cushmanni* Zone (UC3) corresponds in Adolphus D-50 (Fig. 17) to the *Lithraphidites acutum* zone, the interval between the lowest occurrence of *L. acutum* and the lowest occurrence of *Quadrum gartneri*. Sissingh (1978) placed the top of Van Hinte's UC3 slightly below the lowest occurrence of *Q. gartneri* whereas Wonders (1980), put the upper boundary of the *R. cushmanni* Zone slightly above the lowest occurrence of *Q. gartneri*.

Ascoli (1976) recognized his arenaceous foraminiferal *Dorothia* aff. *filiformis-Ammobaculites comprimatus* Zone (Cenomanian-Lower Turonian) in Onondaga E-84 (Fig. 16) and Mic Mac H-86 (Fig. 15). In the Onondaga E-84 well he assigned this zone to the Cenomanian; its top falls within an interval assigned to the Upper Cenomanian-Lower Turonian in the nannofossil analysis. In the Mic Mac H-86 well this zone was dated by Ascoli as probably Turonian-Cenomanian. The top of the *D.* aff. *filiformis-A. comprimatus* zone corresponds in this well to the lowest occurrence of *Marthasterites furcatus*, which marks the base of the Coniacian in the nannofossil stratigraphy. Ascoli (1976) suggested the possibility of a hiatus at 3000 feet in the Mic Mac H-86 well, which would account for (part of) Turonian time, but there is no nannofossil evidence for such a hiatus. In the Triumph P-50 well (Fig. 11) the highest occurrence of *Ammobaculites comprimatus*, dated as questionable Turonian, occurs at the top of the *Quadrum gartneri* Zone (Lower Turonian). The calcareous benthonic foraminiferal *Gavelinopsis cenomanica* Zone (Cenomanian), with some doubt identified by Ascoli (1976) in Wyandot E-53 (Fig. 12), partly corresponds to the *Lithraphidites acutum* zone (Upper Cenomanian).

Ascoli's *Globotruncana helvetica-Praeglobotruncana stephani* Zone (Turonian) matches more or less the *Quadrum gartneri* Zone (Lower Turonian) and the *Eiffellithus eximius* Zone (Upper Turonian) in Onondaga E-84 (Fig. 16) and Wyandot E-53 (Fig. 12). In these wells the top of this foraminiferal zone corresponds to the lowest occurrence of *Kamptnerius*.

The *Globorotalia renzi-G. sigali* Zone (Coniacian) of Ascoli falls roughly between the lowest occurrence of *Marthasterites furcatus* (base Coniacian) and the lowest occurrence of *Rucinolithus hayii* (Upper Santonian). In the Mic Mac H-86 well (Fig. 15) the top of this zone is just below the lowest occurrence of *R. hayii*, but in Wyandot E-53 (Fig. 12) and Onondaga E-84 (Fig. 16) substantially below this horizon. In the Triumph P-50 well (Fig. 11) a hiatus representing Coniacian-Early Santonian time assumed on the basis of the nannofossil stratigraphy, is not confirmed by the foraminiferal analysis, in which a Coniacian interval (*Globotruncana schneegansi* Zone) was identified. Within this interval the highest occurrences of *Globotruncana schneegansi, G. renzi*, and *G. primitiva-concavata* were recorded. It is not clear, however, if all three species range to the top of the zone, which (top) corresponds to the level of the lowest occurrences of *Rucinolithus hayii, Reinhardtites anthophorus, Arkhangelskiella specillata, Lucianorhabdus cayeuxii*, and *Broinsonia furtiva-B. lacunosa*.

In Adolphus D-50 (Fig. 17) a foraminiferal assemblage with *Globotruncana angusticarinata-renzi* was tentatively assigned to Van Hinte's *G. sigali-G.concavata* (UC 7) or *G. concavata-G. elevata* Zones (UC 8). At the same level the lowest occurrence of *Marthasterites furcatus* (= base Coniacian) occurs. Sissingh (1978) put Van Hinte's UC 7 in the middle of his *Micula staurophora* Zone, corresponding to the uppermost Coniacian. Sissingh correlated Van Hinte's UC 8 with the upper part of his *M. staurophora* Zone, his *Reinhardtites anthophorus* Zone and his *Lucianorhabdus cayeuxii* Zone, which together cover the entire Santonian.

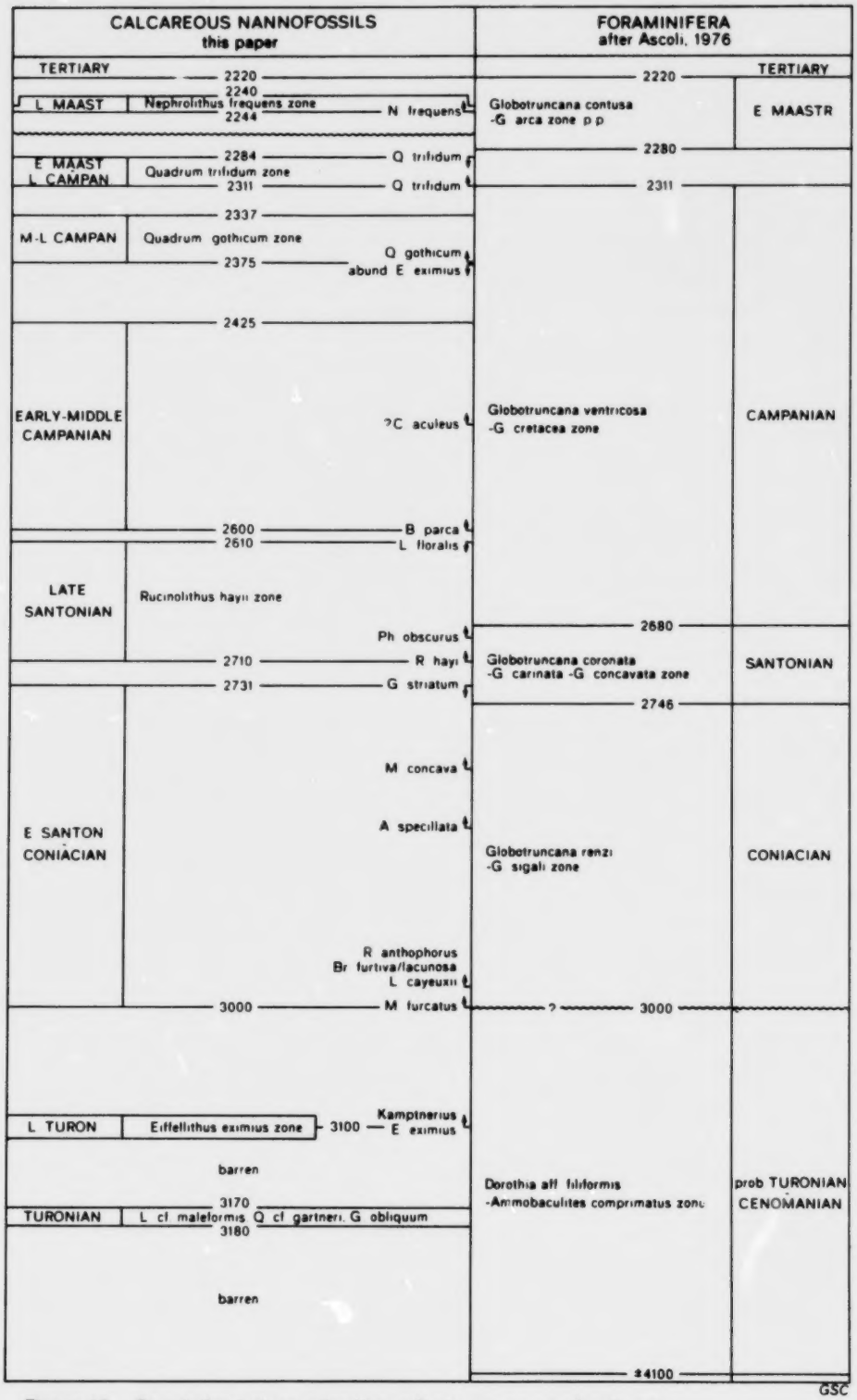

Figure 15. Correlation between the Upper Cretaceous nannofossil and foraminiferal stratigraphies in the Mic Mac H-86 well on Scotian Shelf.

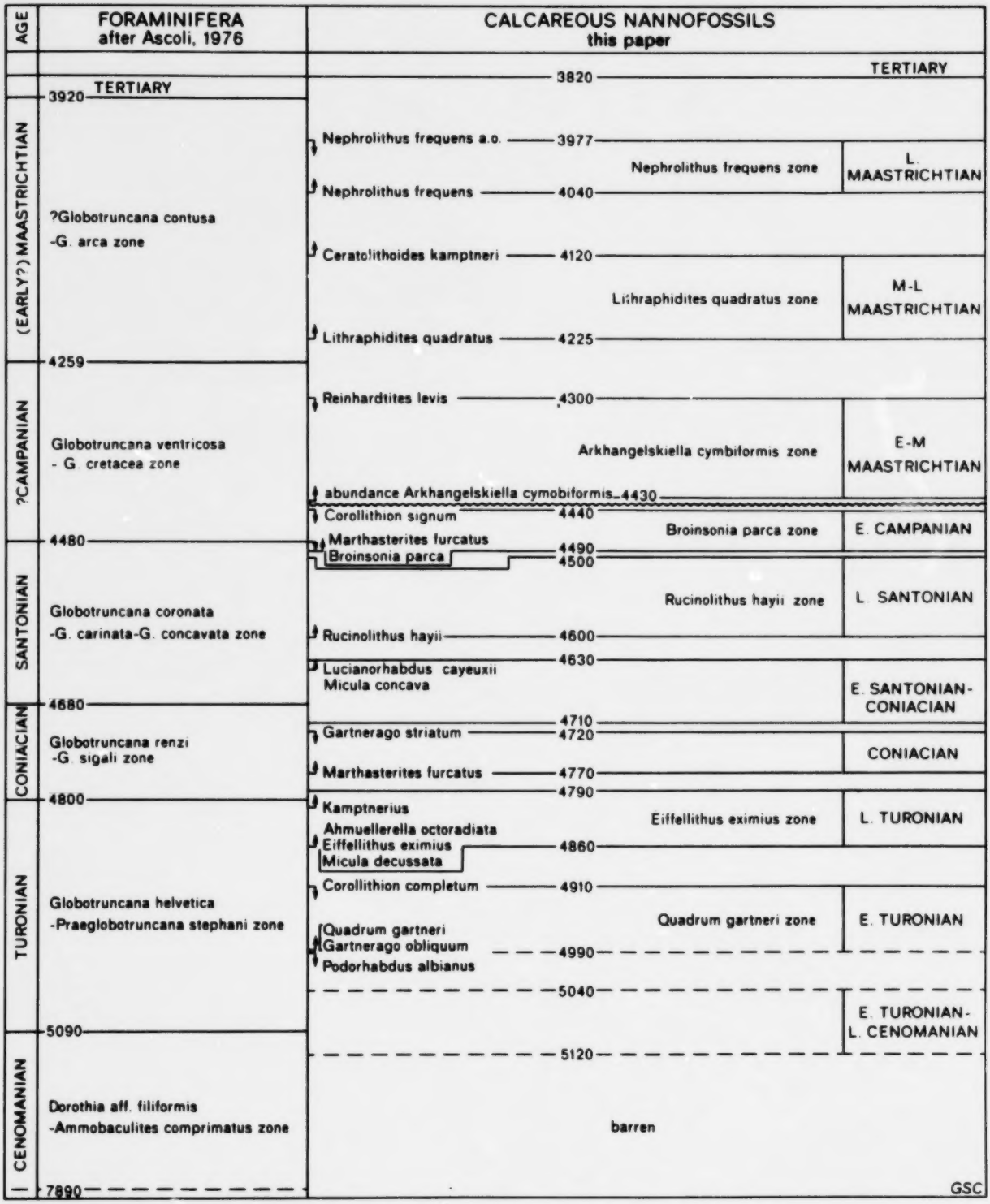

Figure 16. Correlation between the Upper Cretaceous foraminiferal and nannofossil stratigraphies in the Onondaga E-84 well on Scotian Shelf.

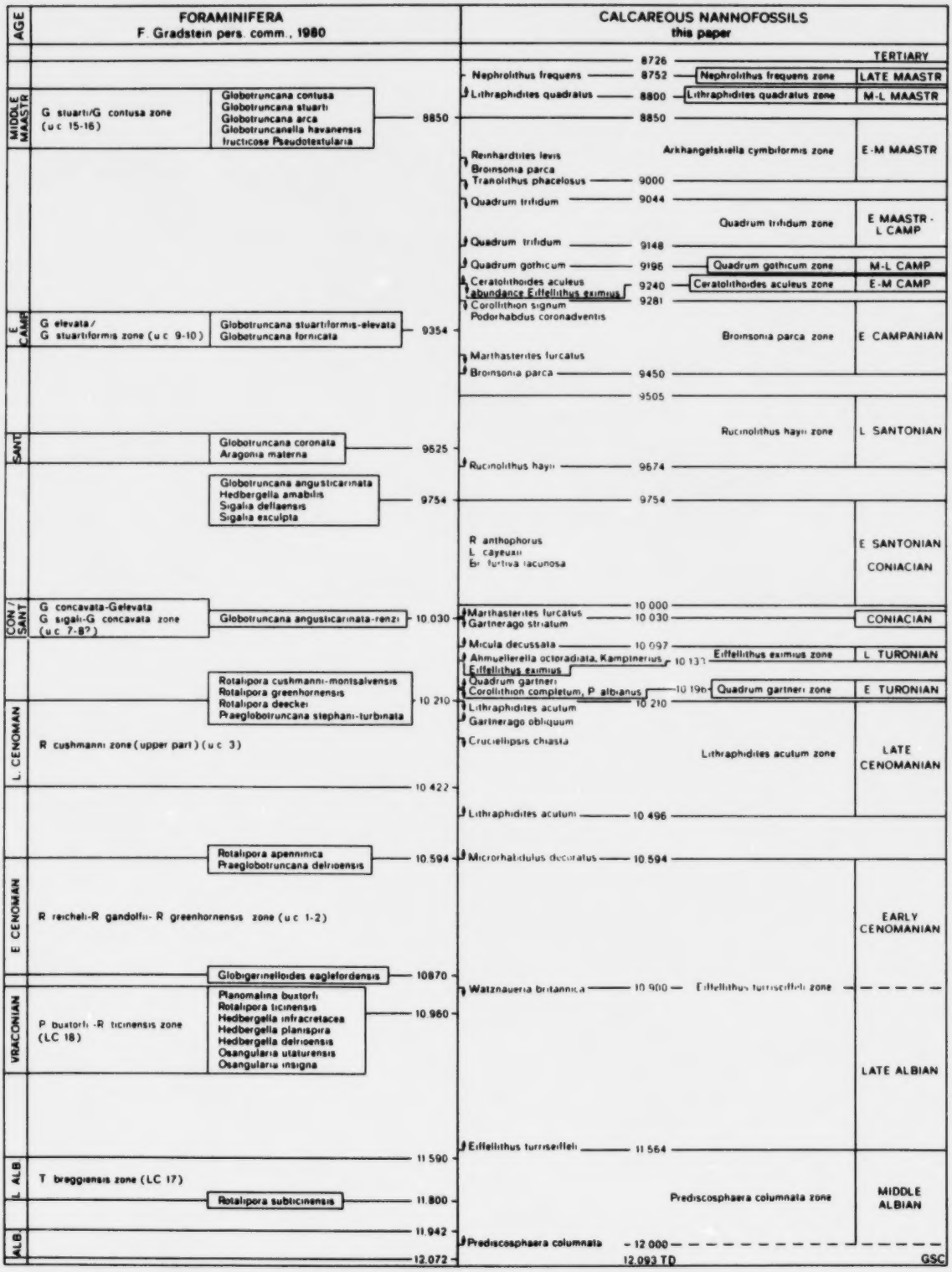

Figure 17. Correlation between the Albian-Maastrichian foraminiferal and nannofossil stratigraphies in the Adolphus D-50 well on northern Grand Banks.

Wonders (1980) placed the lowest occurrence of *G. concavata*, which defines the lower boundary of Van Hinte's *G. sigali-G. concavata* zone (UC 7) at the base of the Santonian, corresponding to the lowest occurrence of *Broinsonia lacunosa*. Van Hinte (1976) put the base of his UC 7 in the mid-Coniacian.

There is a considerable variation in the position of the upper boundary of the Ascoli's (1976) *Globotruncana coronata-G. carinata-G. concavata* Zone (Santonian). In the Onondaga E-84 well (Fig. 16) the top of this zone is just above the lowest occurrence of *Broinsonia parca* (base Campanian), in Mic Mac H-86 (Fig. 15) slightly above the lowest occurrence of *Rucinolithus hayii* (Upper Santonian) and in Wyandot E-53 (Fig. 12), where the zone is poorly defined, below the lowest occurrence of *R. hayii*. In the Triumph P-50 well (Fig. 11) the highest occurrences of *Globotruncana coronata* and *G. concavata*, tentatively dated as Early Santonian by Gradstein (personal communication, 1980), fall within the *Rucinolithus hayii* zone (Upper Santonian). Also in the Adolphus D-50 well (Fig. 17), the top of *G. coronata* occurs above the lowest occurrence of *R. hayii*. The lowest occurence of *Bolivinoides* and the highest occurrence of *Globotruncana angusticarinata-renzi* correspond to the top of the *R. hayii* zone (Upper Santonian) in Triumph P-50.

The position of the top of the Ascoli's *Globotruncana ventricosa-G. cretacea* (Campanian) is highly variable. In Mic Mac H-86 (Fig. 15) it reaches the lowest occurrence level of *Quadrum trifidum* (upper Campanian); in Wyandot E-53 (Fig. 12) it is positioned in the *Broinsonia parca* Zone (Lower Campanian). The upper boundary of the *G. ventricosa-G. cretacea* Zone in Onondaga E-84 (Fig. 16), labelled with a question mark in some of Ascoli's figures, is situated between the highest occurrence of *Reinhardtites levis* and the lowest occurrence of *Lithraphidites quadratus* (middle Maastrichtian). The existence of a hiatus in Onondaga E-84, representing the *Ceratolithoides aculeus* Zone, the *Quadrum gothicum* Zone, and the *Q. trifidum* Zone (which cover together most of the Campanian and part of the Early Maastrichtian), was not diagnosed in the foraminiferal analysis.

In the Triumph P-50 well (Fig. 11) the highest occurrence of *Globotruncana angusticarinata*, which tops an interval assigned to the Lower Campanian, coincides with the lowest occurrence of *Quadrum gothicum* (middle Campanian). In Adolphus D-50 (Fig. 17) a foraminiferal assemblage with *Globotruncana stuartiformis-elevata* and *G. fornicata*, assigned by Gradstein (personal communication, 1980) to Van Hinte's *G. elevata/G. stuartiformis* Zone (UC9-10) falls within the upper part of the *Broinsonia parca* Zone (Lower Campanian), between the highest occurrence of *Marthasterites furcatus* and the lowest occurrence of *Ceratolithoides aculeus*. In the correlation scheme of Sissingh (1978) Van Hinte's UC 9 to 10 cover an interval from the lowest occurrence of *Phanulithus obscurus* (which is below the base of *B. parca*) to the lowest occurrence of *Quadrum trifidum* (Upper Campanian). The *G. elevata* zone of Wonders (1980), which is equivalent to Van Hinte's UC9-10, ranges from just below the entry of *B. parca* to slightly above the entry of *Q. trifidum*.

The *Globotruncana ventricosa-G. stuarti* assemblage (Upper Campanian-Lower Maastrichtian), which completes the Cretaceous sequence in the Triumph P-50 well (Fig. 11), corresponds to the *Quadrum trifidum* Zone.

In most wells the intervals assigned to the Maastrichtian in the foraminiferal and nannofossil stratigraphies are reasonably concordant, but the subdivisions of the Maastrichtian do not always match. Ascoli (1976) recognized only the lower part of his *Globotruncana contusa-G. arca* Zone (Lower Maastrichtian) in Mic Mac H-86, Wyandot E-53, and (probably) in the Onondaga E-84. In Mic Mac H-86 (Fig. 15) it corresponds to an interval in which in the nannofossil analysis, only a thin slice of Upper Maastrichtian sediments (*Nephrolithus frequens* Zone) was encountered. In Onondaga E-84 (Fig. 16) it matches the *Lithraphidites quadratus* Zone and *Nephrolithus frequens* Zone, which cover the upper part of the Maastrichtian in the nannofossil scheme. In the Wyandot E-53 well (Fig. 12) the top of the *G. contusa-G. arca* Zone p.p. (Lower Maastrichtian) falls within the *Quadrum trifidum* zone (Late Campanian-Early Maastrichtian).

In Adolphus D-50 (Fig. 17) a foraminiferal assemblage with *Globotruncana contusa*, *G. stuarti*, *G. arca*, and *Globotruncanella havanensis*, assigned by Gradstein (personal communication, 1980) to the *G. stuarti/G. contusa* Zone (UC15-16) of Van Hinte or to the *G. gansseri* Zone of Postuma (1971), corresponds to the top of the *Arkhangelskiella cymbiformis* Zone (middle Maastrichtian). It occurs well above the highest occurrence of *Reinhardtites levis*, but below the base of *Lithraphidites quadratus*. Sissingh (1978) put the top of Van Hinte's *G. contusa* Zone (UC16) and Postuma's *G. gansseri* Zone just below the highest occurrence of *R. levis*. In Wonders' (1980) scheme the base of Van Hinte's UC15 falls within the lower part of the *L. quadratus* Zone, and the top of UC16 in the lower part of the Upper Maastrichtian *Micula murus* Zone.

The *Globotruncanella mayaroensis* Zone of Van Hinte (Upper Maastrichtian) and many other authors is correlative with the *Nephrolithus frequens* Zone in Indian Harbour M-52 (Fig. 13). Sissingh (1978) equated the *G. mayaroensis* Zone with the interval comprising the uppermost part of his *R. levis*, his *A. cymbiformis*, and *N. frequens* Zones (i.e. approximately the interval from the highest occurrence of *R. levis* to the top of the Cretaceous). Wonders (1980) correlated the *G. mayaroensis* Zone with the upper part of the *Micula murus* Zone, the low latitude equivalent of the *N. frequens* Zone.

As was the case with the palynomorph stratigraphy, the age assignments of the foraminiferal stratigraphy (after Ascoli, 1976) differ considerably from the chronostratigraphic interpretations of the nannofossil analysis in the Mohawk B-93 well (Fig. 9). The top of the *Rotalipora cushmanni-R. greenhornensis* Zone (Upper Cenomanian) is situated above the lowest occurrence of *Eiffellithus eximius* (Upper Turonian). The *Globotruncana helvetica-Praeglobotruncana stephani* Zone (Turonian) falls within the *E. eximius* Zone (Upper Turonian). The upper part of the *Globotruncana renzi-G. sigali* Zone (Coniacian) and the *Globotruncana coronata-G. carinata-G. concavata* Zone (Santonian) correspond to an interval assigned to the Coniacian in the nannofossil stratigraphy. The *Globotruncana ventricosa-G. cretacea* Zone (Campanian) is largely equivalent to an interval interpreted as Santonian on the basis of nannofossils in the Mohawk B-93 well.

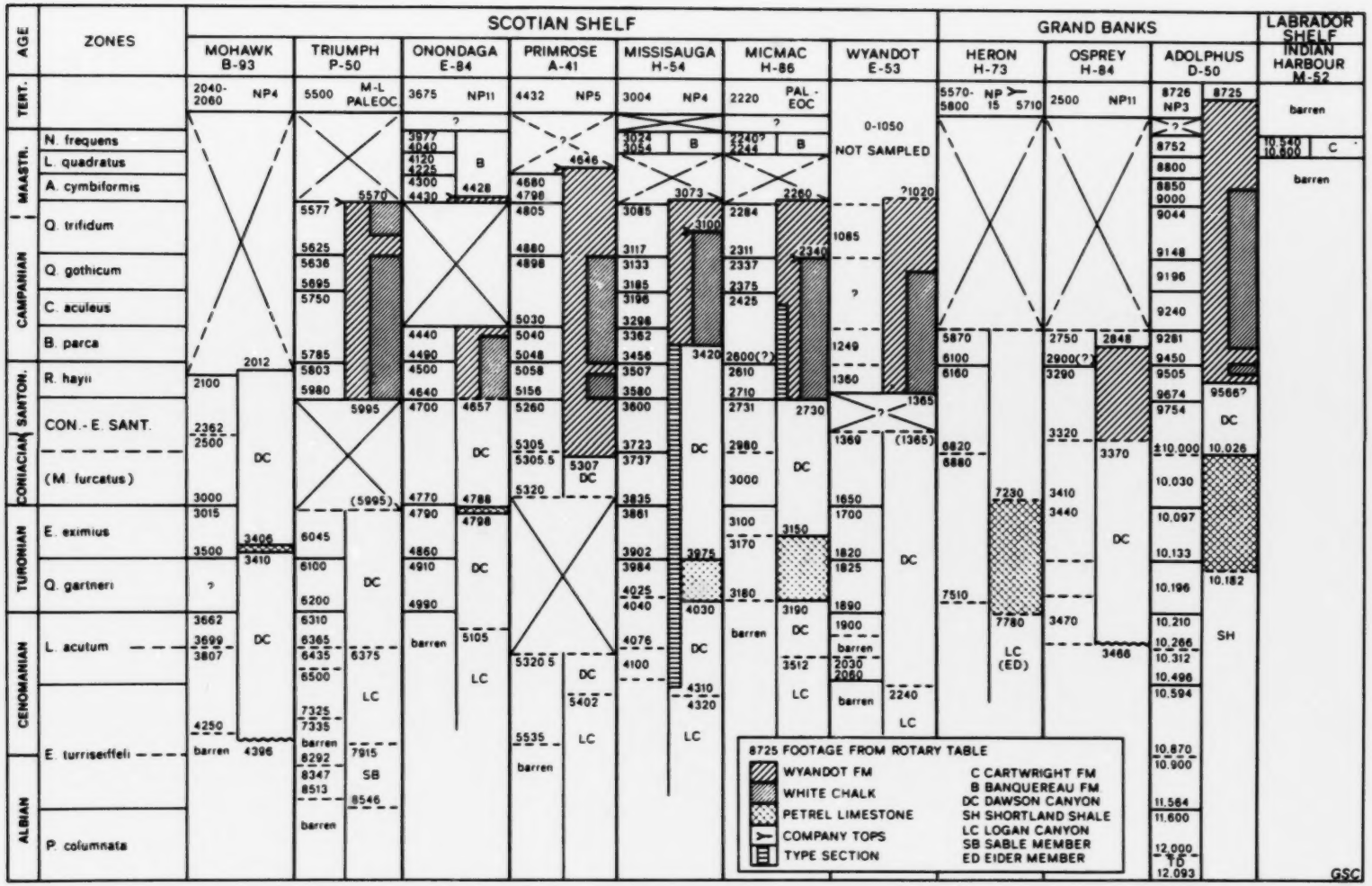

Figure 18. Biostratigraphical and lithostratigraphical correlations of 11 wells on the Canadian Atlantic margin.

STRATIGRAPHIC CORRELATIONS

This section examines the occurrences of the nannofossil zones proposed here in 11 wells on the Canadian Atlantic margin and the correlation of the lithostratigraphy with the zonation. Attention is paid to the hiatuses that occur in the well sections, and to the stratigraphic distribution of the carbonate units, namely the Petrel Member and the Wyandot Formation. Estimates are made of the accumulation rates of the lithological units. The depositional environment and paleoceanographic regime are discussed in the next section.

It may be useful to recall those of the lithostratigraphic units (Fig. 2) that are relevant to the discussion. The approximately mid- Cretaceous Logan Canyon Formation is a sequence of alternating sandstones and silty shales. In it the Sable Member is a local shale tongue, and the Eider Member in the Grand Banks area a sandstone-shale sequence. The Shortland Shale is a lateral (seaward) equivalent of the Logan Canyon Formation (Jansa and Wade, 1975a), sometimes included in the Dawson Canyon Formation (McIver, 1972; Given, 1977). The Dawson Canyon Formation, overlying the Logan Canyon Formation (and the Shortland Shale) is a predominantly shale sequence, silty in the lower part, calcareous in the upper part. The Petrel Member is a limestone unit within the Dawson Canyon Formation. The Wyandot Formation, which overlies the Dawson Canyon Formation, is composed of chalk, sometimes interbedded with marl. It is overlain by the Banquereau Formation, which consists mainly of mudstones. The Cartwright Formation is a predominantly mudstone unit of Late Cretaceous-Paleocene age on the Labrador Shelf.

The nannofossil zones and lithostratigraphic units of the Albian- Maastrichtian rocks of 11 wells on the Canadian Atlantic margin are shown in Figure 18. Footages are from the rotary table. The stratigraphic tops were picked from mechanical logs by J.A. Wade (personal communication, 1980). The figure shows that the nannofossil stratigraphy is most complete in the Adolphus D-50 well (about middle Albian through Maastrichtian). The other extreme is the Indian Harbour M-52 well on the Labrador Shelf, where only the Upper Maastrichtian *Nephrolithus frequens* zone was recognized. The lowest stratigraphic level of nannofossil bearing samples depends on the lithofacies, and in most of the wells considered here it is situated in the lower part of the Dawson Canyon Formation. In the Triumph P-50 well some of the more shaly interbeds in the Logan Canyon Formation and the lower part of the Sable Member contain nannofossils.

Hiatuses

Several hiatuses have been recognized in the 11 wells, which reflect the increased stratigraphic resolution of the nannofossil zonation relative to that using other microfossils. A hiatus probably occurs at the Cretaceous-Tertiary contact in all the wells, but its magnitude varies greatly. Some wells also contain hiatuses within the Upper Cretaceous. Wide sample spacing and/or barren samples sometimes make it impossible to delimit the stratigraphic gaps precisely, and the possibility of condensed sequences between samples, however improbable, can never be ruled out.

The hiatus at the Cretaceous – Tertiary contact represents a period varying from ±2 Ma in Adolphus D-50 to an estimated 27 Ma in Heron H-73 (based on the time scales of Hardenbol and Berggren, 1978; Van Hinte, 1976). The contact can be delimited fairly precisely in the Adolphus D-50 and Mississauga H-54 wells, where samples are closely spaced across it (spacing ±25 feet). In both wells the highest Cretaceous sample has been assigned to the Upper Maastrichtian *Nephrolithus frequens* zone. In the Adolphus D-50 the lowest Tertiary sample belongs to the *Chiasmolithus danicus* Zone (NP3*), indicating that the NP1 and NP2, corresponding to the lower half of the Danian, are missing. In Mississauga H-54 the lowest Tertiary sample was assigned to the *Ellipsolithus macellus* Zone (NP4), suggesting that the entire Danian (NP1-3) is missing.

Far more substantial hiatuses occur at the Cretaceous-Tertiary contact in Mohawk B-93, Heron H-73 and Osprey H-84 wells. In Mohawk B-93 the hiatus appears to account for the Campanian, Maastrichtian and Danian stages. A sidewall core sample from 2100 feet was dated Santonian, and the oldest Tertiary nannofossil assemblage in a cuttings chip sample from 2040-2060 feet, is earliest Thanetian (NP4, *E. macellus* Zone). The nannofossil assemblages found in cuttings chips from higher levels and in a sidewall core from 1880 feet appeared to be all of Early Eocene age (NP10-12). In Heron H-73 the hiatus seems to represent most of Campanian, Maastrichtian, Paleocene and Early Eocene time. The highest studied Cretaceous sample, at 5870 feet, belongs to the *Broinsonia parca* Zone (Early Campanian), and the lowest Tertiary sample, from 5770-5800 feet, was assigned to the *Chiphragmalithus alatus* Zone (NP15, Lutetian). In Osprey H-84 there is no evidence for the top six Cretaceous and the lowest ten Tertiary nannofossil zones, but there is a considerable sample gap, where these zones would occur if they were present in the well. The highest Cretaceous sample, from 2750 feet, was dated Early Campanian (B. parca Zone), and the lowest studied Tertiary sample, from 2500 feet can be referred to the *Discoaster binodosus* Zone (NP11, Early Ypresian).

In the Triumph P-50 well almost the entire Maastrichtian and the Lower Paleocene seem to be missing. The *Quadrum trifidum* Zone (Late Campanian-earliest Maastrichtian) was identified at 5577 feet and a Middle-Late Paleocene nannofossil assemblage was found at 5500 feet. In the Primrose A-41 well no evidence was found for Middle-Late Maastrichtian and Early Paleocene nannofossils, but as in Osprey H-84 the samples are widely spaced across the Cretaceous – Tertiary contact. The *Arkhangelskiella cymbiformis* Zone (Early-Middle Maastrichtian) was recognized at 4680 feet, and the *Fasciculithus tympaniformis* Zone (NP5, Early Thanetian) at 4432 feet.

In Onondaga E-84 and Indian Harbour M-52 the intervals directly above the Upper Maastrichtian *Nephrolithus frequens* Zone contain no nannofossils. In Onondaga E-84 the Early Ypresian *Discoaster binodosus* Zone (NP11) was identified about 300 feet above the top of the Maastrichtian. The *Quadrum trifidum* Zone (Late Campanian – Earliest Maastrichtian) was recognized at 1085 feet in the Wyandot E-53 well, but samples were not available above this.

The relatively refined nannofossil zonation proposed here has permitted the recognition of several disconformities within the Upper Cretaceous that have not been detected by

* NP zones refer to the standard zonation of Martini, 1971. The chronostratigraphic calibration of the Tertiary zones is after Hardenbol and Berggren, 1978.

the foraminiferal and palynological analyses of the same wells. These hiatuses seem to be local phenomena, possibly related to movements of the Upper Triassic or Lower Jurassic salts of the Argo Formation. Some wells have been drilled above (Onondaga E-84 and Primrose A-41) and on the flanks (Heron H-73 and Adolphus D-50) of salt domes.

The stratigraphic position of the hiatuses within the Cretaceous section varies from Upper Cenomanian – Turonian in Primrose A-41 to possibly Lower-Middle Maastrichtian in Missisauga H-54 and MicMac H-86. In the Primrose A-41 the disconformity can be recognized in a conventional core (core 6, from 5300-5326 feet) at about 5320 feet, where it is marked by glauconite. The nannofossil assemblage at 5320 feet was dated as Coniacian. The first 10 cm below the glauconitic level consists of concretionary calcareous shale, in which no nannofossils were found. A sample taken 10 cm below the glauconitic level contains a Late Cenomanian nannofossil assemblage (lower part of the *Lithraphidites acutum* Zone), indicating that the stratigraphic gap accounts for the upper part of the *L. acutum* Zone, the *Quadrum gartneri* Zone and the *Eiffellithus eximius* Zone. A similar hiatus has been recognized in the Sachem D-76 well (Fig. 1, but not in Fig. 18) between 5802 (Coniacian) and 5818 feet (Upper Cenomanian, upper part of the *L. acutum* Zone).

In the Onondaga E-84 well there is a stratigraphic gap between 4440 and 4430 feet. The hiatus represents the *Ceratolithoides aculeus* Zone, the *Quadrum gothicum* Zone and the *Q. trifidum* Zone, which cover most of the Campanian and possibly the lowermost Maastrichtian. In Missisauga H-54 and MicMac H-86 there is possibly an hiatus at the top of the Wyandot Formation. In both wells the *Arkhangelskiella cymbiformis* Zone and the *Lithraphidites quadratus* Zone seem to be missing.

Coniacian and Lower Santonian rocks are assumed to be missing in Triumph P-50 between 6045 and 5980 feet. A poor nannofossil assemblage at 6045 feet has been referred to the Late Turonian *Eiffellithus eximius* Zone, a very rich nannoflora at 5980 feet has been dated Late Santonian (*Rucinolithus hayii* Zone). The disconformity is probably situated at 5995 feet, where the mechanical logs indicate an abrupt change in lithology (the contact between the Dawson Canyon Formation and the Wyandot Formation). The silty character of the shale at 6045 feet also suggests that the more calcareous upper part of the Dawson Canyon Formation is missing in the Triumph P-50 well.

In the Wyandot E-53 well the contact at 1365 feet between the Dawson Canyon Formation and Wyandot Formation may also be marked by an hiatus. The nannofossil assemblage at 1369 feet could not be exactly dated (Coniacian – ? Early Santonian) but differs significantly from the assemblage at 1360 feet, which has been assigned to the *Rucinolithus hayii* Zone (Late Santonian).

It is relevant to point out that at the nearby DSDP location, site 384 on the J-Anomaly ridge on the Grand Banks continental rise (Fig. 1), the sedimentary sequence is continuous across the Cretaceous-Tertiary boundary, but a major unconformity occurs between the Upper Albian and Maastrichtian (Tucholke et al., 1979). At DSDP site 111A on Orphan Knoll (Fig. 1), the Upper Cenomanian to Campanian and the Lower Paleocene are absent (Laughton et al., 1972).

The relationship between the nannofossil zonation and the lithostratigraphic units is discussed below based upon their development in the 11 wells considered in this study.

Logan Canyon Formation and Shortland Shale

Nannofossils were found only in some shaly beds in the upper part of the Logan Canyon Formation in Triumph P-50 and Primrose A-41. In Triumph P-50 the top of the Logan Canyon Formation has been picked at 6375 feet, close to the highest occurrence of *Cruciellipsis chiastia*, halfway up the Upper Cenomanian *Lithraphidites acutum* Zone. Part of the Sable Member of the Logan Canyon Formation is correlative with the lower part of the *Eiffellithus turriseiffeli* Zone (Upper Albian) in the Triumph P-50 well. In Primrose A-41 the top of the Logan Canyon Formation (at 5402 feet) falls within an interval assigned to the upper part of the *E. turriseiffeli* Zone (Lower Cenomanian) or the lower part of the *L. acutum* Zone (lower Upper Cenomanian).

In the other wells the top of the Logan Canyon Formation is situated 100 to 300 feet below the lowest datable sample, probably in the Cenomanian; possibly in the Upper Cenomanian in Onondaga E-84, possibly in the Lower Cenomanian in Missisauga H-54 and Wyandot E-53.

The Shortland shale, an informal unit introduced by Jansa and Wade (1975a) as a lateral equivalent of the Logan Canyon Formation, but considered by Given (1977) as Dawson Canyon Shales, top in the *Quadrum gartneri* Zone (Lower Turonian) and extend downward in the Adolphus D-50 well at least into the Mid-Albian *Prediscosphaera columnata* Zone.

Dawson Canyon Formation

McIver (1972) designated the interval from 3420 to 4310 feet in the Missisauga H-54 well as the type section for the Dawson Canyon Formation. The base of this interval, corresponding to the top of the underlying Logan Canyon Formation, falls within the Cenomanian, possibly in the lower half, while the top lies in the *Broinsonia parca* Zone (Lower Campanian).

In most wells the top of the Dawson Canyon Formation is positioned in the Santonian; in Triumph P-50, MicMac H-86, Adolphus D-50 and probably in Onondaga E-84 in the Upper Santonian *Rucinolithus hayii* Zone. The top of the formation is marked by a disconformity in Triumph P-50, Mohawk B-93, Heron H-73 and probably in Wyandot E-53. In Triumph P-50, where the upper part of the formation probably is missing, the formation tops in the *Eiffellithus eximius* Zone (Upper Turonian). In Wyandot E-53 the top of the formation falls within an interval dated as Coniacian -?Early Santonian.

In Mohawk B-93 and Heron H-73 the Dawson Canyon shales form the top of the Cretaceous section. The formation top in Mohawk B-93 is situated in the Santonian, in Heron H-73 probably in the *Broinsonia parca* Zone (Lower Campanian). In the Primrose A-41 well the top of the Dawson Canyon Formation, picked at 5307 feet is in the Coniacian.

Petrel Member

A carbonate unit usually referred to as the Petrel Limestone occurs in the Dawson Canyon Formation. The term

"Petrel limestone" was informally introduced by Amoco-Imperial (1973) for a persistent geophysical and geological limestone marker in the Grand Banks area. On the eastern Scotian Shelf a "thin but very persistent calcareous marker near the middle of the Dawson Canyon Shale", consisting of fossiliferous chalk, marl or calcareous mudstone, was described by McIver (1972). These carbonate units beneath the Grand Banks and Scotian Shelf were formally designated the Petrel Member of the Dawson Canyon Formation by Jansa and Wade (1975a), who described the carbonates as varying in lithology from skeletal wackestone to coccolith chalk and mudstone (Jansa and Wade, 1975b). The thick Petrel Limestone in the Grand Banks area has been described by Swift et al. (1975) as most commonly a clean, white to light grey, microcrystalline to cryptocrystalline limestone.

According to Upshaw et al. (1974) the Petrel Limestone ranges in age from Late Albian to early Senonian, according to Jansa and Wade (1975b; based on data of Williams, 1975 and Jenkins et al., 1974) it is Turonian beneath the southern Scotian Shelf and Turonian-Coniacian beneath the southwestern Grand Banks.

In stratigraphical practice discrete calcareous units on the mechanical logs that appear to fall within the Turonian-Coniacian interval, are assigned to the Petrel Member, but it is not certain that these units on the Scotian Shelf can indeed be correlated with each other or with the Petrel Limestone in the Grand Banks area.

In the Scotian Shelf wells (Fig. 18), the Petrel Member is thin (4 to 55 feet). It falls within the Upper Turonian *Eiffellithus eximius* Zone in the Mohawk B-93 and Onondaga E-84 wells, and within the Lower Turonian *Quadrum gartneri* Zone in the Missisauga H-54 well. The Petrel Member in the MicMac H-86 well has been dated (undifferentiated) Turonian. The Petrel Member was not identified in Triumph P-50, Primrose A-41, and Wyandot E-53.

The absence of the Petrel Member in Triumph P-50 and Primrose A-41 may be due to a disconformity. In Triumph P-50 the assumed hiatus representing Coniacian-Early Santonian time may also cover part of the late Turonian. The stratigraphic gap in Primrose A-41 accounts for the Late Cenomanian-Turonian.

On the southern Grand Banks the Petrel Member is absent in Osprey H-84, but represented by a thick limestone sequence in Heron H-73 (7230- 7780? feet). The sequence in Heron H-73 consists of two limestone units separated by a 60 foot shaly interval. Swift et al. (1975) assigned the upper unit (7230-7580 feet) to the Petrel Limestone and termed the lower unit (7640-7780 feet) "Heron Limestone". The Heron Limestone is white to reddishbrown, microcrystalline to medium grained, and has a macroporosity (as opposed to the microporosity of the Petrel Limestone) (Swift et al. 1975). According to L. Jansa (personal communication, 1980) the top of the Heron Limestone (at 7640 feet) is marked by a disconformity. The limestones could not be accurately dated, but most of the upper unit (7230-7510 feet) falls somewhere within the Turonian-Coniacian interval.

In the Adolphus D-50 well, on the northern Grand Banks, the interval from 10 026 to 10 182 feet, which forms the basal part of the Dawson Canyon Formation and consists of alternating limestone and marl beds, has been referred to the Petrel Member. The top of this interval is situated in the Coniacian, the base probably in the Lower Turonian *Quadrum gartneri* Zone.

Wyandot Formation

The term "Wyandot Chalk" was formally introduced by McIver (1972) for a distinctive and, on the Scotian Shelf, widely recognized Upper Cretaceous chalky carbonate unit, which grades both laterally and vertically from pure chalk to marl. Jansa and Wade (1975a) used the term "Wyandot Formation" and defined it as a dominantly chalk formation with marl and calcareous shale interbeds. They described the chalk as "composed almost exclusively of coccoliths with minor amounts of small calcareous foraminifers, sponge spicules and pelecypod, ammonite and *Inoceramus* fragments." Jansa and Wade stated further that in the higher shelf areas (toward the landward edge of the basin) the formation is coarser grained and composed of fine silt-sized foraminiferal packestone that grades upward into chalky carbonate, and that near the present shelf edge the chalk is interbedded with marls.

The Wyandot Formation has been interpreted variously in the literature, where it does not always include the marls. In Figure 18 I have indicated the approximate stratigraphic position of the more typical white chalks, the top and bottom of the Wyandot Formation (bottom = top of the Dawson Canyon Formation) as picked by the Geological Survey of Canada (J. Wade, personal communication, 1980), and the Wyandot tops as reported in the oil company well history reports (Open File, Department of Energy, Mines and Resources, Ottawa). The thickness of the Wyandot Formation depends on the lithostratigraphical interpretation; the typical white chalks usually are 300 to 400 feet thick. The stratigraphic position of the Wyandot Formation in each of the wells in Figure 18 is discussed below.

The interval from 2440 to 2730 feet in the MicMac H-86 well has been designated by McIver (1972) the type section for the Wyandot Chalk. However, the top of this section at 2440 feet lies exactly 100 feet below the actual top of the chalk and presumably represents a typographical error. The top of the chalk (at 2340 feet), taken in the well history report (Shell, 1972c) as the top of the Wyandot Formation, falls within the Middle-Upper Campanian *Quadrum gothicum* Zone. The top of the Wyandot Formation sensu lato, picked at 2260 feet, is probably situated in the Upper Campanian-lowermost Maastrichtian *Quadrum trifidum* Zone (identified at 2284 feet). The base of the formation (top Dawson Canyon Formation), at 2730 feet, is in the Upper Santonian *Rucinolithus hayii* Zone in MicMac H-86. In the Triumph P-50 well the Wyandot Formation (white chalks) is unconformity bounded at top and bottom. The top belongs to the Upper Campanian-lowermost Maastrichtian *Q. trifidum* Zone, the bottom to the Upper Santonian *R. hayii* Zone.

In the Onondaga E-84 well the top of the Wyandot Formation has been picked at 4428 feet, just above the disconformity between 4440 and 4430 feet, and falls within the Lower-Middle Maastrichtian *Arkhangelskiella cymbiformis* Zone. It is probable, however, that there is a difference in depth calibration between the mechanical logs and the sidewall cores, and that the disconformity marks the top of the Wyandot Formation. In that case the formation top would be situated in the lower Campanian *Broinsonia parca* Zone. The base of the formation falls within the Santonian, probably in the Upper Santonian *Rucinolithus hayii* Zone, in the Onondage E-84 well.

In the Primrose A-41 well the top of the Wyandot Formation has been picked at 4646 feet, approximately corresponding to the middle Maastrichtian (the Lower-Middle Maastrichtian *A. cymbiformis* Zone was identified in the 4680-4798 foot interval). The base of the formation has been placed at 5307 feet and falls within the Coniacian. According to J. Wade (personal communication, 1980) the base corresponds to the top of the Dawson Canyon Formation, according to the well history report (Shell, 1975) it corresponds to the top of the Logan Canyon Formation (Dawson Canyon Formation absent). The white coloured chalk in Primrose A-41 covers a much thinner interval, topping in the *Quadrum gothicum* Zone (Middle-Upper Campanian), bottoming in the *Rucinolithus hayii* (Upper Santonian).

In the Missisauga H-54 well the top of the Wyandot Formation sensu lato (at 3073 feet) and the top of the white chalk (picked as formation top by Shell, 1972b), which is situated slightly lower (at 3100 feet), both fall within the *Quadrum trifidum* Zone (Upper Campanian-lowermost Maastrichtian). The base of the formation is in the *Broinsonia parca* Zone (Lower Campanian).

No samples were available from the 0-1050 foot interval of Wyandot E-53, but the top of the Wyandot Formation sensu lato has been tentatively picked at 1020 feet and can be dated as Late Campanian or younger (the Upper Campanian-lowermost Maastrichtian *Q. trifidum* Zone was identified at 1085 feet). The top of the white chalk lies somewhat lower in an undated interval. The base of the formation in this well is probably marked by a disconformity and occurs within the Upper Santonian *Rucinolithus hayii* Zone.

The Wyandot Formation is not present in the Mohawk B-93 well. The absence may be due to a lateral facies change but could also be caused by a disconformity. Although in the palynological and foraminiferal analyses a Campanian interval was identified in Mohawk B-93, the youngest encountered Cretaceous assemblages in the nannofossil analysis appeared to be of Santonian age, in other words possibly pre-Wyandot.

In the Heron H-73 well the top of the Wyandot Formation was picked at 5710 feet by Austin Exploration Ltd. (1975). This level corresponds to the top of an Eocene chalk. According to J. Wade (personal communication, 1980) the Wyandot Formation is not present in this well.

The Wyandot Formation in the Osprey H-84 well is composed of nannofossil marlstone with intercalations of calcareous shale and siltstone (Jansa et al., 1977). The top of this unit falls within the *Broinsonia parca* Zone (Lower Campanian), the base possibly within the Santonian.

In the Adolphus D-50 well, on the northern Grand Banks, the top of the Wyandot Formation sensu lato has tentatively been picked at 8725 feet, a level that is here correlated with the Lower Paleocene *Chiasmolithus danicus* Zone (NP3). The top of the white chalk falls within the *Arkhangelskiella cymbiformis* Zone (Lower-Middle Maastrichtian). The chalk samples (sidewall cores) from 9044 to 9240 feet are red (not caused by drilling mud contamination). The base of the Wyandot Formation in this well is within the Upper Santonian *Rucinolithus hayii* Zone.

The chronostratigraphic distribution of the Wyandot Formation depends to an extent upon its definition, but on the Scotian Shelf the formation usually ranges in age from Late Santonian (*Rucinolithus hayii* Zone) to Late Campanian-Earliest Maastrichtian (*Quadrum trifidum* Zone). On the northern Grand Banks (Adolphus D-50) it reaches into the Maastrichtian and possibly into the Paleocene.

A chalk unit at DSDP site IIIA on Orphan Knoll, which may be correlated with the Wyandot Formation (McIver, 1972; Jansa and Wade, 1975a), is of Maastrichtian age (Laughton, et al., 1972). This sequence is about 10 m thick, bounded above and below by unconformities, and consists of brownish white chalky nannofossil-foraminiferal ooze in which echinoderm spines and *Inoceramus* fragments are common (Laughton et al., 1972).

At DSDP site 384 on the J-anomaly ridge on the Grand Banks continental rise, an apparently uninterrupted Maastrichtian-Paleocene chalky sequence has been cored. The unit is almost 100 m thick and bounded by unconformities above and below. The lower part of the sequence (Maastrichtian) has been described as a nannofossil chalk, the upper part (Paleocene) as a nannofossil chalk and ooze, with fewer nannofossils at the base (Tucholke et al., 1979).

Accumulation Rates

By correlating the lithological units with the nannofossil zonation it is possible to estimate the accumulation rate per unit. The chronostratigraphic calibration of the nannofossil stratigraphy has already been discussed. Accumulation rates are expressed in centimetres per 1000 years (cm/ka), based on the time scale of Van Hinte (1976).

The accumulation rates in a few wells are illustrated in Figure 19. In these diagrams the depth (sediment thickness) has been plotted against time; the slope of the curve expresses the sediment accumulation rate.

The following approximate accumulation rates (not corrected for compaction) have been calculated:

Sable Member of the Logan Canyon Formation: ± 7 cm/ka (Triumph P-50)

Logan Canyon Formation (upper part; not including the Sable Member): ± 10 cm/ka (Triumph P-50)

Shortland Shale (as far as penetrated in Adolphus D-50): ± 4 cm/ka

Dawson Canyon Formation: in most Scotian Shelf wells 1-1.5 cm/ka, in Mohawk B-93 ± 3 cm/ka, in Adolphus D-50, (Dawson Canyon shales above Petrel Member): 2-2.5 cm/ka.

Petrel Member: slightly less than 1 cm/ka ("0.8") in Adolphus D-50.

Wyandot Formation: on Scotian Shelf 1-1.5 cm/ka; in Adolphus D-50 1.5-2 cm/ka.

The accumulation rates calculated for the Wyandot chalk agree fairly well with the rates given for the Maastrichtian-Paleocene chalk at DSDP site 384 (J-anomaly ridge): varying from 0.6 to 2.0 cm/ka (Tucholke et al., 1979). Ruffman and Van Hinte (1973) reported the rather low accumulation rate of 0.3 cm/ka for the Maastrichtian chalk at DSDP site IIIA on Orphan Knoll. Hakansson et al. (1974) computed a remarkable 15 cm/ka for the Maastrichtian chalk in Denmark.

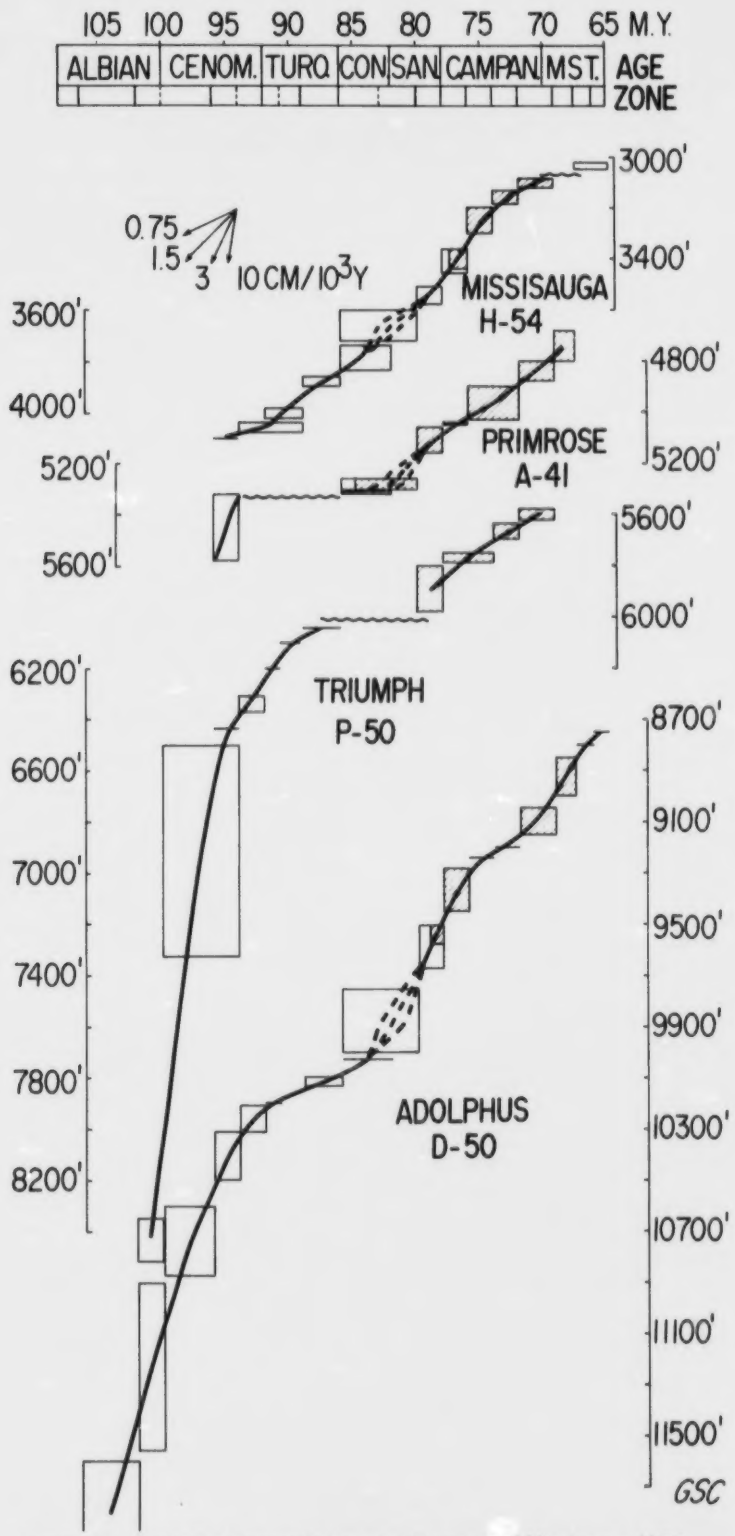

Figure 19. Sediment accumulation rate diagrams of Missisauga H-54, Primrose A-41, Triumph P-50 (Scotian Shelf) and Adolphus D-50 (northern Grand Banks). Depth (sediment thickness) is plotted against time (absolute time scale after Van Hinte, 1976). The slope of the curves expresses the sediment accumulation rate. Cross hatching indicates the Wyandot Formation.

PALEOECOLOGY

Paleobiogeographical variations in nannoplankton assemblages are well documented for the Quaternary (McIntyre and Bé, 1967; McIntyre et al., 1972) and Tertiary (Haq and Lohmann, 1976; Haq, 1980) but are less well known for the Cretaceous. During most of the Cretaceous there seems to have been little difference between high latitude and low latitude nannoplankton floras. In the latest Cretaceous increased temperature gradients between high and low latitudes were responsible for increased provinciality among calcareous nannoplankton (Roth, 1978).

Worsley and Martini (1970) demonstrated provincialism of the Late Maastrichtian species *Micula murus* (low latitudes) and *Nephrolithus frequens* (high latitudes). Thierstein (1976) compared Mesozoic nannofossil assemblages from many widely dispersed localities and distinguished high latitude (boreal-austral), low latitude (tropical), and hemipelagic (marginal) species. *Nannoconus* spp., *Corollithion exiguum* and *Micula murus* were amongst others, considered (sub)tropical. *Cribrosphaerella primitiva, Kamptnerius magnificus, Lucianorhabdus cayeuxii* and *Nephrolithus frequens* were classified as boreal-austral. *Gartnerago obliquum, Micula staurophora, Ahmuellerella octoradiata, Phanulithus obscurus* (s.l.), and *Braarudosphaera bigelowii* were shown to become more abundant with increasing paleolatitude. Marginal species include *Nannoconus* spp., *Lithastrinus floralis, Lucianorhabdus cayeuxii* and *Braarudosphaera bigelowii*.

Thierstein and Haq (1977) analyzed Maastrichtian and Danian nannoplankton assemblages quantitatively. Some of their conclusions were: (a) relative abundances at any particular site remained remarkably steady throughout the Maastrichtian, suggesting relatively stable ecological conditions; (b) Maastrichtian biogeographic boundaries roughly parallel latitudes; (c) tropical assemblages are characterized by the numerical predominance of *Micula staurophora* and *Watznaueria barnesae* and by common *Micula murus* (Late Maastrichtian) and *Ceratolithoides aculeus;* (d) higher latitude communities contain abundant *Nephrolithus frequens* (Latest Maastrichtian), *Arkhangelskiella cymbiformis, Kamptnerius magnificus, Lucianorhabdus cayeuxii* and *Reinhardtites anthophorus*.

Wind (1979) recognized distinct Campanian-Maastrichtian nannofossil provinces in the southern Atlantic and Indian oceans. Low latitude regions were characterized by abundant *Biscutum constans, Watznaueria barnesae* and *Cyclagelosphaera margereli*, higher latitudes by *Biscutum magnum* and *B. coronum*, and an abundance of *Micula staurophora*. In the southernmost DSDP sites in the Atlantic and Indian oceans *W. barnesae, C. margereli* and *M. staurophora* were extremely rare. Wind suggested the ratios of high latitude to low latitude species of *Biscutum* and of *M. staurophora* to *W. barnesae* and *C. margereli* as a tool to delineate water masses.

Roth (1978) characterized *Micula murus, Quadrum gothicum* and *Quadrum trifidum* as warm water species; *Nephrolithus frequens, Lithraphidites quadratus* and *L. praequadratus* as relatively cold water species.

Depositional environments in the Scotian basin have been interpreted on the basis of planktonic and benthonic foraminifera and ostracods by Ascoli (1976). He inferred that environmental conditions fluctuated between continental and outer neritic during the Albian and Cenomanian, and that open marine sedimentation was more frequent in the Cenomanian. The depositional environment in the Turonian and Coniacian was depicted as inner to outer neritic, in the Santonian as outer neritic to bathyal. The Campanian-Maastrichtian environments were interpreted as "prevailing bathyal sometimes outer neritic".

Table 3: Footage, type and age of samples used in the (quantitative) paleoecological analysis.

AGE	ZONE	SCOTIAN SHELF												GRAND BANKS				LABRADOR SHELF	
		TRIUMPH P-50		ONONDAGA E-84		PRIMROSE A-41		MISSISAUGA H-54		MICMAC H-86		WYANDOT E-53		EMERILLON C-56		ADOLPHUS D-50		INDIAN HARBOUR M-52	
		footage	sample type	footage	sample type	footage	sample type	footage	sample type	footage	sample type	footage	sample type	footage	sample type	footage	sample type	footage	sample type
MAASTRICHTIAN	N. frequens			3977	SWC					2244	SWC					8752	SWC	10540 10570	CTS CTS
	L. quadratus			4120	SWC											8800	SWC		
	A. cymbiformis			4300	SWC	4680 4798	CORE CORE							3900	CTS	8850	SWC		
CAMPANIAN	Q. trifidum	5577 5625	SWC SWC			4805 4846	CORE CORE	3104	SWC	2284 2311	SWC SWC	1085	SWC	3920	CTS	9044 9148	SWC SWC	SWC = SIDEWALL CORE CTS = CUTTINGS FRAGMENT	
	Q. gothicum					4955	SWC												
	C. aculeus	5750	SWC					3298	SWC	2425	SWC					9240	SWC		
	B. parca											1249	SWC						GSC

In this study some simple quantitative and qualitative observations were made about the frequency distribution and diversity of the mid-AlbianMaastrichtian nannoplankton species from the Canadian Atlantic margin. In the quantitative analysis the relative abundances of species (based on a count of 400 specimens) were determined in 29 samples from the Campanian- Maastrichtian interval in nine wells located on the Scotian Shelf, Grand Banks, and Labrador Shelf. Table 3 shows the wells, ages, footages and the type of the samples considered. Most samples were sidewall cores. From Emerillon C-56 and Indian Harbour M-52 individual cuttings fragments were analyzed. Four of the five samples from Primrose A-41 were core samples. The Early-Middle Campanian samples were from the *Ceratolithoides aculeus* Zone in Triumph P-50, Missisauga H-54, and Adolphus D-50; from the *C. aculeus* or *Quadrum gothicum* Zones in Primrose A-41; from the *Broinsonia parca* or *C. aculeus* Zones in MicMac H-86; and from the *B. parca* Zone in Wyandot E-53.

The distribution of species in the Campanian-Maastrichtian interval is discussed below, followed by a consideration of distribution patterns in the Albian-Santonian interval and an examination of the species diversity.

Campanian-Maastrichtian

Distribution of Species

To illustrate the relative abundances of the nannofossil species in the Campanian-Maastrichtian interval, the percentages obtained in the Adolphus D-50 well are presented in Table 4. Values are shown for taxa that form at least 2 per cent of the nannofossil assemblage in one or more samples.Some species are grouped: *Cribrosphaerella* includes *C. ehrenbergii* and *C. pelta*; *Micula "staurophora"* embodies *M. decussata* and *M. concava*; *Phanulithus* comprises *P. obscurus* and *P. ovalis*; and *Reinhardtites* embraces *R. anthophorus* and *R. levis*. Separate counts were not made for species of *Biscutum*. The table shows that *Watznaueria barnesae* (especially in the lower three samples), *Micula "staurophora"*, *Prediscosphaera cretacea* and *Arkhangelskiella cymbiformis* (in the upper three samples) are the most abundant species. With some exceptions (e.g. the relative frequency of *Lucianorhabdus cayeuxii*) the same is broadly true for the other wells. The frequency pattern of some abundant and supposedly facies susceptible species was examined in detail.

Table 4: Quantitative distribution (in percentages) of the most important nannofossil species in the Campanian-Maastrichtian of Adolphus D-50.

ADOLPHUS D-50													
AGE	ZONE	A. cymbiformis	Biscutum spp.	Cribrosphaerella	E. eximius	E. turriseiffeli	L. cayeuxii	M. staurophora	Phanulithus	P. cretacea	Reinhardtites	W. barnesae	Z. spiralis
MAASTR.	N. frequens	17.5	1.5	3	–	7.25	–	26.5	–	13.5	–	11	3.25
	L. quadratus	16.5	4.75	4	–	4.75	0.25	19.75	–	25.25	–	8.75	3.5
	A. cymbiformis	14.5	7	2	–	4.75	0.75	19.75	–	22.75	–	7	4.25
CAMP.	Q. trifidum	0.25 0.5	1.25 8	6 2.25	– –	4 6	7.75 4.5	24 10	2 –	10 18.25	2 1.5	24.75 30.25	– 0.25
	C. aculeus	–	2.5	0.75	4.75	2.25	2.25	8	1	22	2.25	36.75	0.5

GSC

The relative frequency of *Watznaueria barnesae* and *Micula "staurophora"* and the ratio between the two species in the nine wells is given in Table 5. *W. barnesae* decreased during the Campanian- Maastrichtian. In the Lower-Middle

Table 5: Relative abundances (in percentages) of *M. staurophora* and *W. barnesae* and the frequency ratio between these two species (M/W) in the Campanian-Maastrichtian of 9 wells on the Canadian Atlantic margin.

		SCOTIAN SHELF																GRAND BANKS						LABRADOR SHELF		
		TRIUMPH P-50			ONONDAGA E-84			PRIMROSE A-41			MISSISAUGA H-54			MICMAC H-86			WYANDOT E-53			EMERILLON C-56			ADOLPHUS D-50			INDIAN HARBOUR M-52		
AGE	ZONE	M. staurophora	W. barnesae	M/W	M. staurophora	W. barnesae	M/W	M. staurophora	W. barnesae	M/W	M. staurophora	W. barnesae	M/W	M. staurophora	W. barnesae	M/W	M. staurophora	W. barnesae	M/W	M. staurophora	W. barnesae	M/W	M. staurophora	W. barnesae	M/W	M. staurophora	W. barnesae	M/W
MAASTRICHTIAN	N. frequens				24	6.25	3.8							16.25	7.5	2.1							26.5	11	2.4	26.5 37.25	2.25 0.75	11.8 49.7
	L. quadratus				15.25	11.25	1.3																19.75	8.75	2.3			
	A. cymbiformis				24.75	13.25	1.9	17.5 19	11.5 10.75	1.5 1.8										7.5	5.25	1.4	19.75	7	2.8			
CAMPANIAN	Q. trifidum	27.5 9	24.5 32.75	1.1 0.3				10.5 11.5	12.5 16	0.8 0.7	9.25	21.75	0.4	9 7.5	10.5 11	0.9 0.8	8	11.75	0.7	20.75	16	1.3	24 10	24.75 30.25	1.0 0.3			
	EARLY-MIDDLE CAMPANIAN	6.5	34.25	0.2				21.75	35.5	0.6	1.25	29.75	0.04	9.75	27.25	0.4	3	26.5	0.1				8	36.75	0.2			

GSC

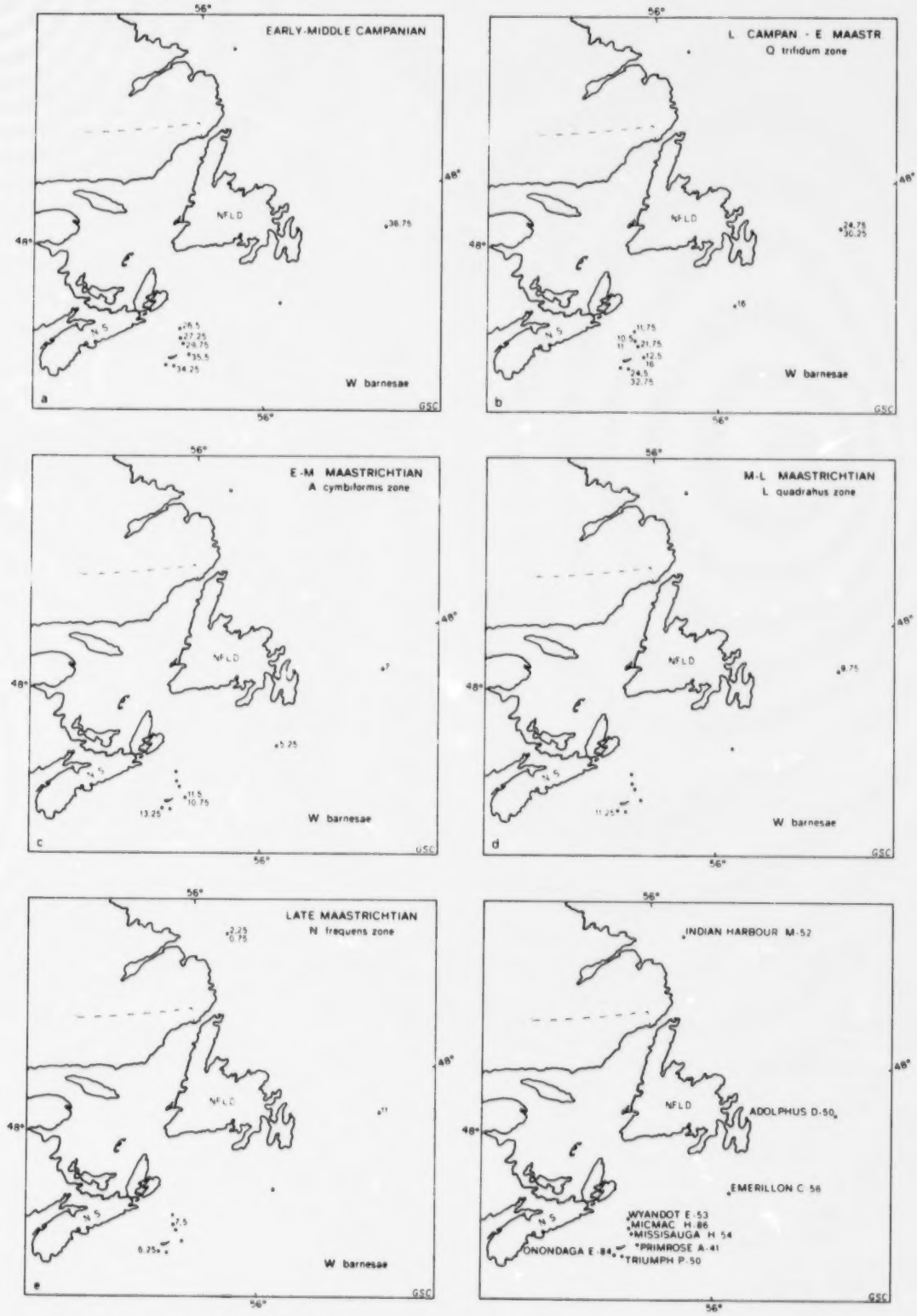

Figure 20. Geographical plots of the relative abundance of *Watznaueria barnesae* expressed as percentages for the Campanian-Maastrichtian interval.

Campanian the species scores about 30 per cent, in the Maastrichtian it drops below 10 per cent, with minimum values of 0.75 to 2.25 per cent in Indian Harbour M-52 on the Labrador Shelf. The scores are, of course, relative and will be influenced by fluctuations in the percentages of other species. *Prediscosphaerea cretacea*, for example, is one of the most abundant species, but its relative frequency varies greatly, from 7.5 to 28 per cent (Table 6). Its peak abundances in Primrose A-41 (at 4846, 4805, and 4798 feet), in MicMac H-86 (at 2311 and 2284 feet), in Emerillon C-56 (*A. cymbiformis* Zone) and Adolphus D-50 (at 8850 and 8800 feet) suppress the percentages of *W. barnesae* and presumably are, at least partly, responsible for irregularities in the trend of *W. barnesae*.

The geographic distribution of *W. barnesae* is shown in Figure 20. In Figure 20a the Lower-Middle Campanian percentages are plotted. *W. barnesae* scores high in all the nine wells. There is possibly a slight offshore trend: the percentages appear to increase with distance from (the present) coast. Also in the *Quadrum trifidum* Zone (Upper Campanian- Lowermost Maastrichtian; Fig. 20b) the lowest values are found closest to the coast. For some wells two samples from the *Q. trifidum* Zone were examined quantitatively; in each case the stratigraphically higher of the two samples yielded the smallest percentages. In the *Arkhangelskiella cymbiformis* Zone (Lower-Middle Maastrichtian; Fig. 20c) the relative frequency values of *W. barnesae* are somewhat lower for the Grand Banks than for the Scotian Shelf. The *Lithraphidites quadratus* Zone (Middle-Upper Maastrichtian) was identified only in two wells (Fig. 20d). In the *Nephrolithus frequens* zone (Upper Maastrichtian; Fig. 20e) the overall scores of *W. barnesae* are low, with an absolute minimum of 0.75 per cent in the most northerly of the nine wells, Indian Harbour M-52 on the Labrador Shelf.

Micula "staurophora" (embracing *M. decussata* and the rare *M. concava*) shows roughly the opposite stratigraphic distribution to *W. barnesae* (Table 5). Its relative abundance is generally greater in the Maastrichtian than in the Campanian. Its trend toward an increasing abundance upward is more erratic, however, than the trend toward decreasing abundance upward of *W. barnesae*. An abnormally large percentage of *M. "staurophora"* occurs, for example, in the Lower-Middle Campanian of Primrose A-41. In Triumph P-50 and Adolphus D-50 a remarkable increase in the abundance of *M. "staurophora"* occurs in the *Quadrum trifidum* Zone, the percentages increasing 2.5 to 3 times. The score of *M. "staurophora"* remains high in the Maastrichtian in Adolphus D-50.

Figure 21 shows the geographic frequency distribution of *M. "staurophora"* from Early-Middle Campanian through Late Maastrichtian time. In the Middle-Late Maastrichtian (*L. quadratus* Zone; Fig. 21d) and Late Maastrichtian (*N. frequens* Zone; Fig. 21e) *M. "staurophora"* was more abundant in the more northerly wells.

Wind (1979) recognized latitudinal trends in the relative frequencies of *Micula staurophora*, *Watznaueria barnesae* and *Cyclagelosphaera margereli* in the Maastrichtian in the southern Atlantic and Indian oceans. Since he considered that dissolution might have led to selective preservation of these solution-resistant species, he used the ratio of *M. staurophora* to *W. barnesae* + *C. margereli* (M/W + C) to

Table 6: Relative abundance of *Prediscosphaera cretacea* (in percentages) in the Campanian-Maastrichtian of 9 wells on the Canadian Atlantic margin.

AGE	Relative abundance P.cretacea / ZONE	SCOTIAN SHELF						G.B.	EAST NFLD.	LABR. SHLF.
		TRIUMPH P-50	ONONDAGA E-84	PRIMROSE A-41	MISSISAUGA H-54	MICMAC H-86	WYANDOT E-53	EMERILLON C-56	ADOLPHUS D-50	INDIAN HARBOUR M-52
MAASTRICHTIAN	N. frequens		9			11.5			13.5	10.75 20.25
	L. quadratus		15						25.25	
	A. cymbiformis		16.25	15 27.75				26.5	22.75	
CAMPAN	Q. trifidum	13.5 15		25.5 22	15.75	27.25 21.25	17	14	10 18.25	
	EARLY-MIDDLE CAMPANIAN	10.75		9.25	19	13.75	7.5		22	

GSC

delineate water masses. Because this ratio may serve as a general standard to define Late Cretaceous water masses, I have calculated the M/W + C values for the 29 samples, even though dissolution is of minor importance in our material. *C. margereli* was rarely found, so the M/W + C factor in this analysis expresses essentially the ratio of *M. "staurophora"* to *W. barnesae* (M/W).

The M/W values are given in Table 5 and more convincingly expressed in a bar diagram in Figure 22. The ratio shows a rising trend through the Campanian-Maastrichtian interval. In the Lower-Middle Campanian M/W values range from 0.04 to 0.6. The Lower-Middle Campanian samples are not all coeval. They are from the *C. aculeus* Zone in Triumph P-50 (M/W:0.2), Missisauga H-54 (M/W:0.04), and Adolphus D-50 (M/W:0.2); from the *C. aculeus* or *Quadrum gothicum* Zones in Primrose A-41 (M/W:0.6); from the *Broinsonia parca* or *C. aculeus* Zones in MicMac H-86 (M/W:0.4); and from the *B. parca* Zone in Wyandot E-53 (M/W:0.1). In the *Quadrum trifidum* Zone (Upper Campanian-lowermost Maastrichtian) M/W values vary from 0.3 to 1.3. Within this zone the M/W ratio increases sharply from 0.3 to 1.1 in Triumph P-5 and to 1.0 in Adolphus D-50, respectively, a consequence largely of the sudden increase of *Micula "staurophora"*. In the *Arkhangelskiella cymbiformis* and *Lithraphidites quadratus* Zones M/W varies from 1.3 to 2.8. In the Upper Maastrichtian *Nephrolithus frequens* Zone M/W ranges from 2.1 to 49.7.

The biggest jumps in the M/W ratio occur between the *Q. trifidum* and *A. cymbiformis* Zones in Primrose A-41 (from 0.8 to 1.8) and Adolphus D-50 (from 1.0 to 2.8), and between the *L. quadratus* and *N. frequens* Zones in Onondaga E-84 (from 1.3 to 3.8).

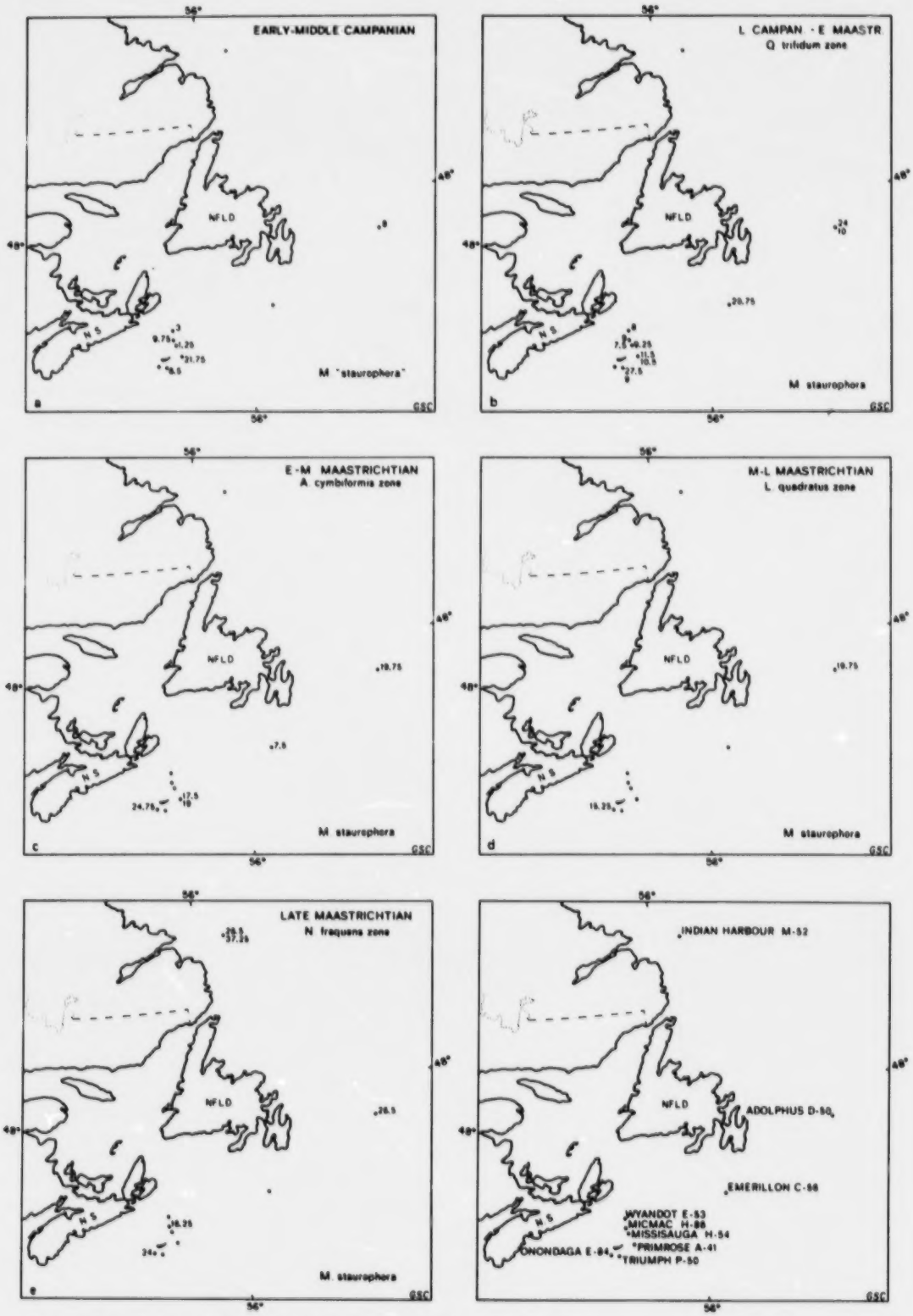

Figure 21. Geographical plots of the relative abundance of *Micula "staurophora"* (*M decussata* + *M. concava*) expressed as percentages for the Campanian Maastrichtian interval.

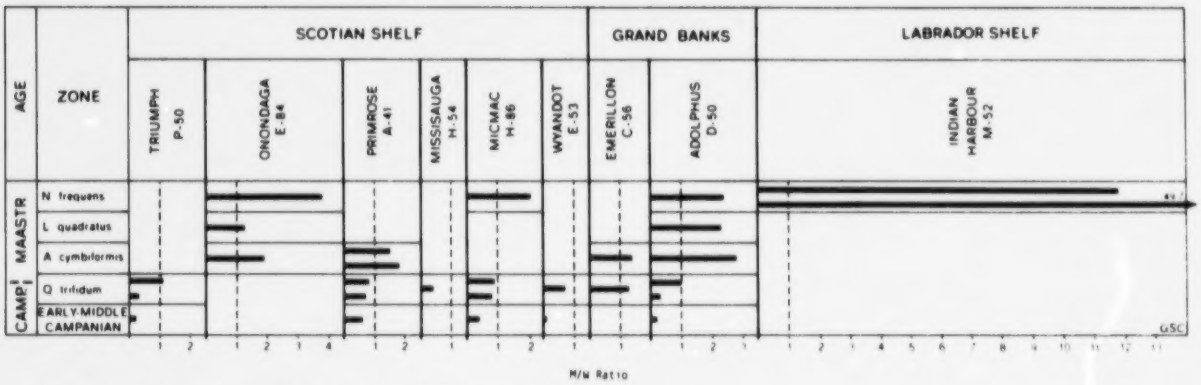

Figure 22. Bar diagrams showing the frequency ratios of *M. "staurophora"* (*M. decassata* + *M. concava*) to *W. barnesae* (M/W) in the Campanian-Maastrichtian.

Figure 23 plots the *M. staurophora*/*W. barnesae* ratio geographically. In Lower-Middle Campanian (Fig. 23a) and in the *Q. trifidum* zone (Fig. 23b) there is no difference between the M/W values for the Scotian Shelf and for the northern Grand Banks (Adolphus D-50). In the *A. cymbiformis* Zone (Fig. 23c) and *L. quadratus* Zone (Fig. 23d) M/W values are higher for the northern Grand Banks. In the *N. frequens* Zone (Fig. 23e) the M/W ratio is in the same order of magnitude on the Scotian Shelf and northern Grand Banks, but very much higher on the Labrador Shelf.

Arkhangelskiella cymbiformis is abundant in the Maastrichtian (see Table 7). In Adolphus D-50 it increases slowly from 14.5% in the *A. cymbiformis* Zone to 17.5% in the *N. frequens* Zone. In Onondaga E-84 the species increases sharply from 3.75% in the *A. cymbiformis* Zone to 21% in the *L. quadratus* Zone. *A. cymbiformis* scores in the *A. cymbiformis* Zone considerably higher on the Grand Banks (Emerillon C-56 and Adolphus D-50) than on the Scotian Shelf (Onondaga E-84 and Primrose A-41). In the *N. frequens* Zone *A. cymbiformis* is less abundant on the Labrador Shelf (Indian Harbour M-52) than in the basins to the south.

Table 7: Relative abundances (in percentages) of *Arkhangelskiella cymbiformis* and *Kamptnerius magnificus* in the Campanian-Maastrichtian of 9 wells on the Canadian Atlantic margin.

AGE	ZONE	SCOTIAN SHELF												GRAND BANKS				LABRADOR SHELF	
		TRIUMPH P-50		ONONDAGA E-84		PRIMROSE A-41		MISSISAUGA H-54		MICMAC H-86		WYANDOT E-53		EMERILLON C-56		ADOLPHUS D-50		INDIAN HARBOUR M-52	
		Arkhangelskiella cymbiformis	*Kamptnerius magnificus*	*Arkhangelskiella cymbiformis*	*Kamptnerius magnificus*	*Arkhangelskiella cymbiformis*	*Kamptnerius magnificus*	*Arkhangelskiella cymbiformis*	*Kamptnerius magnificus*	*Arkhangelskiella cymbiformis*	*Kamptnerius magnificus*	*Arkhangelskiella cymbiformis*	*Kamptnerius magnificus*	*Arkhangelskiella cymbiformis*	*Kamptnerius magnificus*	*Arkhangelskiella cymbiformis*	*Kamptnerius magnificus*	*Arkhangelskiella cymbiformis*	*Kamptnerius magnificus*
MAASTRICHTIAN	N. frequens			18.25	7.5					17	2.25					17.5	1.75	14.75 9	19.5 4.25
	L. quadratus			21	1.25											16.5	1.75		
	A. cymbiformis			3.75	1.25	8 2.5	1.75 0.25							10.5	1	14.5	0.5		
CAMPAN.	Q. trifidum	0.5 ~	0.5 2			2.5 0.25	0.5 —	~	1.25	~	0.5 0.5	~	1.75	4	—	0.25 0.5	0.25 —		
	EARLY-MIDDLE CAMPANIAN	~	0.5			~	0.5	~	0.25	~	0.25	~	0.25			~	0.25		GSC

Table 8: Relative abundances (in percentages) of *Lucianorhabdus cayeuxii* and *Phanulithus* in the Campanian-Maastrichtian of 9 wells on the Canadian Atlantic margin.

AGE	ZONE	SCOTIAN SHELF										GRAND BANKS				LABRADOR SHELF	
		TRIUMPH P-50		ONONDAGA E-84		PRIMROSE A-41		MISSISAUGA H-54		MICMAC H-86		WYANDOT E-53		EMERILLON C-56		ADOLPHUS D-50		INDIAN HARBOUR M-52	
		L. cayeuxii	Phanulithus	L. cayeuxii	Phanulithus	L. cayeuxii	Phanulithus	L. cayeuxii	Phanulithus	L. cayeuxii	Phanulithus	L. cayeuxii	Phanulithus	L. cayeuxii	Phanulithus	L. cayeuxii	Phanulithus	L. cayeuxii	Phanulithus
CAMPAN. / MAASTRICHTIAN	N. frequens			~	—											~	—	~	—
	L. quadratus			~	—											0.25	—		
	A. cymbiformis			~	—	~ 0.5	— 0.5							~	0.5	0.75	—		
	Q. trifidum	4.75 1.25	1.75 —			2.5 3.5	0.5 2.75	2	1	1.25 2.25	3.75 5.75	0.75	2.75	0.25	0.25	7.75 4.5	2 —		
	EARLY-MIDDLE CAMPANIAN	12.5	1.5			13.5	1.5	12.25	9.25	21	5.5	13.5	2			2.25	1		GSC

In the nine wells considered *Kamptnerius magnificus* occurs from Upper Turonian through Maastrichtian, but generally is rare below the Maastrichtian. The relative frequency distribution in the Campanian- Maastrichtian is given in Table 7. Only in the *N. frequens* Zone *K. magnificus* scores more than 2%, with peaks of 7.5% in Onondaga E-84 on the Scotian Shelf and of 19.5% in Indian Harbour M-52 on the Labrador Shelf.

Lucianorhabdus cayeuxii, *Phanulithus obscurus*, and *P. ovalis* range from Santonian to ± middle Maastrichtian, but are generally only abundant in the Wyandot Formation (usually Upper Santonian-Upper Campanian/Lower Maastrichtian). The relative abundances of *L. cayeuxii* and *Phanulithus* (*P. obscurus* and *P. ovalis* taken together) in Campanian and Maastrichtian are shown in Table 8. Percentages of *L. cayeuxii* are highest in the Lower- Middle Campanian on the Scotian Shelf (12.5 to 21%). On the northern Grand Banks (Adolphus D-50) *L. cayeuxii* peaks in the *Q. trifidum* Zone, but its maximum score of 7.75% is considerably lower than the maximum percentages on the Scotian Shelf. The highest percentages of *Phanulithus* are recorded in the Lower-Middle Campanian in Missisauga H-54 (9.25%) and MicMac H-86 (5.5%), and in the Q. *trifidum* Zone in MicMac H-86 (5.75% and 3.75%).

Nephrolithus frequens marks the Upper Maastrichtian in the studied wells. Apart from two doubtful specimens (in Missisauga H-84 and MicMac H-86) *Micula murus* was not found. *N. frequens* scores above 1% in Onondaga E-84 (3.75%) and Indian Harbour M-52 (6.75%).

Within the *N. frequens* Zone in Indian Harbour M-52 (Labrador Shelf) two different assemblages can be distinguished (Table 9). They differ in the relative frequency of the species, but not in the species content. The most notable changes (from the lower to the upper assemblage) are: a very large increase in *Kamptnerius magnificus* (from 4.25 to 19.5%); a substantial rise in *Arkhangelskiella cymbiformis* (from 9 to 14.75%); a sharp decline in *Nephrolithus frequens* (from 6.75 to 1%); a near halving of *Prediscosphaera cretacea* (from 20.25 to 10.75%); and a considerable decrease in *Micula "staurophora"* (from 37.25 to 26.5%). Both assemblages consist of the same 25 or so species. Samples above the upper assemblage (at 10 540 feet) contained no nannofossils.

Table 9: Quantitative distribution of the most important nannofossil species (in percentages) in 2 successive assemblages in the *Nephrolithus frequens* zone (Late Maastrichtian) in Indian Harbour M-52 (Labrador Shelf).

INDIAN HARBOUR M-52	A. cymbiformis	Biscutum spp	Cribrosphaerella	E. turriseiffeli	K. magnificus	M. staurophora	N. frequens	P. cretacea	P. spinosa	W. barnesae
10,510'	—	—	—	—	—	—	—	—	—	—
assemblage 2 10,540'	14.75	2.25	2.75	5	19.5	26.5	1	10.75	0.75	2.25
assemblage 1 10,570'	9	0.75	2	3	4.25	37.25	6.75	20.25	3	0.75

GSC

The frequency pattern of *Eiffellithus eximius* is remarkable in that the species "suddenly" (viz. from one sample to another) becomes scarce or absent around the mid-Campanian. On the Scotian Shelf the change from common to rare occurs within the *Quadrum gothicum* Zone in MicMac H-86 and Missisauga H-54, in an interval assigned to the

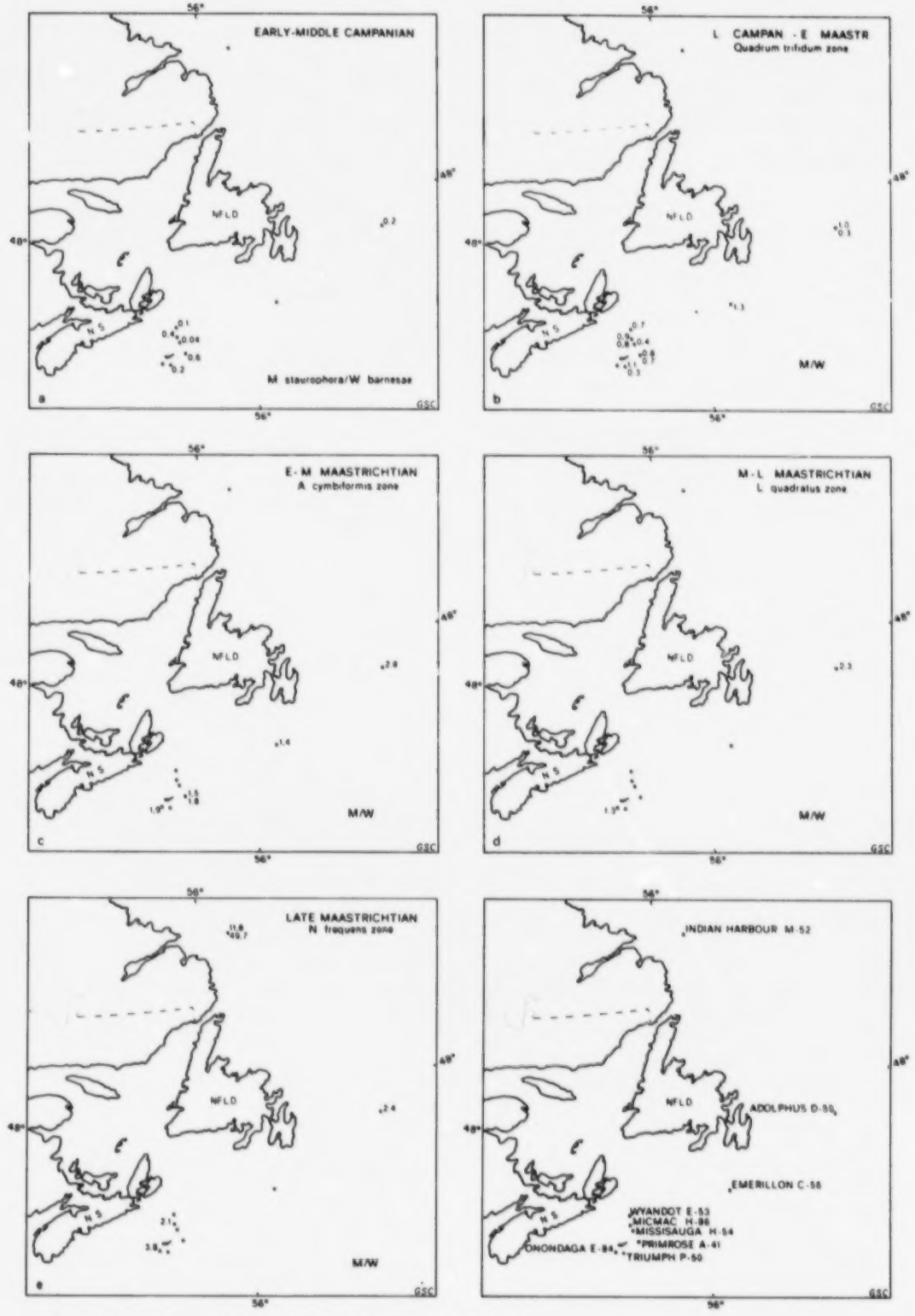

Figure 23. Geographical plots of the frequency ratios of *M. "staurophora"* (*M. decussata* + *M. concava*) to *W. barnesae* (M/W) in the Campanian-Maastrichtian.

Ceratolithoides aculeus-Q. gothicum Zones in Primrose A-41, and in the *C. aculeus* Zone in Triumph P-50. The event is not necessarily diachronous on the Scotian Shelf. Sample spacing is sometimes wide and *Q. gothicum*, a rare species, may have been missed at its actual lowest occurrence level. In other Scotian Shelf and southern Grand Banks wells the highest common occurrence of *E. eximius* is suppressed due to disconformities (i.e. in Mohawk B-93, Onondaga E-84, Heron H-73, and Osprey H-84) or poor sample control (Wyandot E-53). In Adolphus D-50 (northern Grand Banks) *E. eximius* scores as high as 4.75% in the *C. aculeus* Zone, at 9240 feet (Table 4), but was not found in the next highest sidewall core sample (9196 feet, *Q. gothicum* Zone). Higher in Adolphus D-50 only rare specimens of *E. eximius* were recorded in the *Arkhangelskiella cymbiformis* Zone.

The presence of "*Tetralithus*" *copulatus* is surprising on the Canadian Atlantic margin. The species is common in the Campanian- Maastrichtian at DSDP sites 217 and 249 in the Indian Ocean and seems to be restricted to paleolatitudes from 30° to 40°S (Wind, 1975). Specimens were found sporadically in the *Q. trifidum* Zone in Adolphus D-50, Primrose A-41, MicMac H-86, and Missisauga H-54. All have a very large, massive, cross- like distal structure. This morpho-type was reported by Wind (1975) from the same interval (Upper Campanian-Lower Maastrichtian). About 70 Ma ago the Scotian Shelf-Grand Banks area was situated between latitudes 35° and 40°N (Firstbrook et al., 1979).

Other reportedly facies-susceptible species were recorded during this study. *Lithraphidites quadratus* (cold water; Roth, 1978) scores higher than 1% in Adolphus D-50 (*N. frequens* Zone; 1.75%), MicMac H-86 (*N. frequens* Zone; 3.2%), and Onondaga E-84 (*L. quadratus* Zone; 2.5%). For *Lithraphidites praequadratus* (cold water; Roth, 1978) no values greater than 1% were found. *Braarudosphaera bigelowii* (boreal-austral, marginal; Thierstein, 1976) occurs in (very) low numbers in the Campanian- Maastrichtian. *Biscutum coronum* and *B. magnum* (high latitudes; Wind, 1979) were not recognized. *Quadrum trifidum* and *Q. gothicum* (warm water; Roth, 1978) usually are rare, especially the latter. *Q. trifidum* scored more than 1% in one sample (Adolphus D-50, 9044 feet; 1.5%). The possibility of a depressed highest occurrence for *Q. trifidum* has already been discussed.

The distribution patterns can be summarized as follows. *Watznaueria barnesae* decreases steadily from around 30% in the Lower-Middle Campanian to less than 10% in the Upper Maastrichtian with a minimum score of 0.75% in the Maastrichtian of the Labrador Shelf. *Micula "staurophora"* is distributed somewhat irregularly, but is more abundant in the Maastrichtian than in the Campanian. The *M. staurophora/W. barnesae* ratio increases in the upper Campanian in each of the nine wells considered, but the values vary from well to well. In the Lower Maastrichtian the M/W values jump above 1.0. The highest ratios are generally recorded in the Upper Maastrichtian; on the Labrador Shelf M/W is ten times higher than on the Scotian Shelf and Grand Banks. Through the Maastrichtian *Arkhangelskiella cymbiformis* becomes abundant, and *Kamptnerius magnificus* increases in abundance, peaking in the Upper Maastrichtian (with a top score on the Labrador Shelf). *Nephrolithus frequens* is present (and sometimes common) in the Upper Maastrichtian, but *Micula murus* is absent. *Lucianorhabdus cayeuxii* shows a distinct abundance peak in the Lower-Middle Campanian on the Scotian Shelf; on the northern Grand Banks it scores its highest percentages in the *Q. trifidum* Zone. Above the *Q. trifidum* Zone *L. cayeuxii* is rare or absent. *Eifellithus eximius* almost disappears from the record in the *C. aculeus* Zone on the northern Grand Banks and around the entry level of *Q. gothicum* on the Scotian Shelf.

Discussion

Micula "staurophora", *Kamptnerius magnificus*, *Arkhangelskiella cymbiformis*, and *Nephrolithus frequens* are all restricted to, or abundant only in, higher latitudes (Thierstein, 1976; Thierstein and Haq, 1977; Wind, 1979; Worsley and Martini, 1970). *Watznaueria barnesae* dominates tropical assemblages, but decreases in frequency in higher latitudes (Thierstein and Haq, 1977; Wind, 1979). The observed frequency trends in the Campanian-Maastrichtian may be interpreted therefore as reflecting a cooling of the oceanic water along the Canadian Atlantic margin, that climaxed in the Late Maastrichtian and was most severe on the Labrador Shelf.

Lucianorhabdus cayeuxii and *Phanulithus obscurus* (sensu lato) were classified by Thierstein (1976) as marginal (hemipelagic) and high latitude species. Since these two species do not follow the trend of the other high latitude indicators and are generally lacking in the Maastrichtian, they have to be considered as hemipelagic rather than as 'cold water' forms. Accordingly, the peak abundances of *L. cayeuxii* and *Phanulithus* in the Lower-Middle Campanian on the Scotian Shelf would suggest a relatively nearshore environment.

The sudden decline in frequency of *Eiffellithus eximius* approximately in the Mid-Campanian is difficult to explain. Nothing has been published about the ecology of this species. The abrupt change in the abundance of *E. eximius*, which may have occurred slightly earlier on the northern Grand Banks than on the Scotian shelf, may reflect a deteriorating climate.

When did the apparent cooling trend begin? The increasing M/W ratios during the late Campanian and possibly the sharp decline in frequency of *E. eximius* might indicate cooling began around the mid- Campanian. However, although in each well the M/W ratio in the *Q. trifidum* Zone is higher than in the Lower-Middle Campanian, the M/W values vary considerably. The M/W in the *Q. trifidum* Zone in one well is sometimes lower than the M/W in the Lower-Middle Campanian in another (nearby) well (e.g. Triumph P-50 and Primrose A-41). Evidence for a drop in water temperature is more convincing in the Early Maastrichtian (around the extinction datum of *Q. trifidum*), when *A. cymbiformis* and *K. magnificus* (to a lesser degree) became more abundant and a distinct jump in the M/W ratio took place (an M/W ratio of 1.0 may be taken as a 'critical value').

To put the suggested cooling trend in a wider context and to make some paleo-oceanographic speculations, let us consider the situation at the nearest DSDP locations, Sites 111A and 384. The data from Site 111A are derived from Laughton et al. (1972), those from Site 384 are from Tucholke et al. (1979).

At DSDP Site 111A on Orphan Knoll (north-northeast of Adolphus D-50) an unconformity bounded, largely Maastrichtian chalk sequence is present. The base of the chalk unit is situated in the *Q. trifidum* Zone. Only qualitative data are available about the nannoplankton flora. *N. frequens* is not present; a few specimens of *Micula murus* have been found in the top water of a core. *L. cayeuxii* is present and *K. magnificus* is common (Perch-Nielsen, 1972). The common occurrence of *K. magnificus* was interpreted by Perch-Nielsen (1972) as indicating a relatively nearshore environment. The foraminiferal faunas with single and double keeled *Globotruncana, Globotruncanella, Ventrilabrella* and other pseudotextulariids were characterized by Ruffman and Van Hinte (1973) as relatively warm water faunas.

At DSDP Site 384, on the southern continental rise of the Grand Banks, an unconformity-bounded Maastrichtian-Paleocene chalk unit has been cored. The relative abundances of the nannofossil species at Site 384 are given in Figure 24 (after Thierstein and Okada, 1979). *W. barnesae* scores around 20%, *M. staurophora* around 10%, giving M/W values of approximately 0.5. *K. magnificus* is very rare and, apart from one peak of ± 15%, *A. cymbiformis* scores very low percentages. *N. frequens* and *M. murus* both occur, but the latter is more regularly found and less rare. From these frequency distributions the Maastrichtian nannoplankton assemblages of Site 384 can be interpreted as warm water floras.

The chalk accumulation at DSDP Sites 111A and 384 was preceded by long periods of nondeposition (Laughton et al., 1972, and Tucholke et al., 1979, respectively). At Site 111A the chalk is underlain by sandy limestone of Albian-Cenomanian age. At Site 384 the chalk overlies an Upper Barremian-(?)Lower Albian bioclastic limestone. In contrast, on the Scotian Shelf the chalk deposition came to an end in the Late Campanian- Early Maastrichtian (*Q. trifidum* Zone). Younger Maastrichtian sediments often are absent (either by nondeposition or by erosion) or incompletely represented (fine clastics). On the northern Grand Banks the chalk sedimentation seems to have lasted slightly longer. In Adolphus D-50 the white chalks are replaced by marly sediments in the *A. cymbiformis* Zone.

An important event in the history of the Atlantic Ocean is the opening of the Labrador Sea. Srivastava (1978) demonstrated that spreading between Greenland and the North American plate started during magnetic anomaly 32. Following Heirtzler et al. (1968) Srivastava dated this event at 75 Ma (Mid-Campanian). Gradstein and Srivastava (1980) revised the age of the magnetic anomaly 32 to 70 Ma (base Maastrichtian) by extrapolating from the Paleogene polarity time scale of Berggren et al. (1978).

It seems reasonable to assume a relationship between the events which took place in the Early Maastrichtian in the Northwest Atlantic: the establishment of a strait between the Arctic and Atlantic oceans, the cooling of the Northwest Atlantic marginal waters, and the change in sedimentation pattern. The opening of the Labrador Sea would have caused a re-arrangement of water masses and circulation patterns in the Northwest Atlantic Ocean. This could have brought cooler waters southwards and might have led to a shift of the chalk sedimentation from the Scotian shelf and Grand Banks to areas farther offshore (e.g. Orphan Knoll and the southern Grand Banks continental rise). The tropical character of the planktonic faunas and floras at DSDP Sites 111A and 384 indicates that the cold-water influence was restricted to the area of the present Canadian Atlantic margin and that a warm watermass existed farther offshore. Such a circulation pattern would resemble today's Gulf Stream configuraton. In the Maastrichtian the colder water mass reached at least as far south as Onondaga E-84.

These interpretations agree fairly well with the paleooceanographic model of Gradstein and Srivastava (1980). Gradstein and Srivastava postulated on foraminiferal evidence a seaway between the Atlantic and Arctic oceans in the Maastrichtian with surface circulation toward the Arctic. The foraminiferal data are from exploratory wells on the Grand Banks and Labrador Shelf, from DSDP Sites 111 and 112 (Labrador Sea), and from West Greenland (Nugssauq). The foraminiferal fauna from Orphan Knoll (DSDP Site 111A) was described as open marine tropical, that from the northern Grand Banks as "much less explicit tropical with shallower and particularly less oceanic influences". The foraminiferal assemblages from the Labrador Shelf and West Greenland were characterized as temperate and impoverished. Gradstein and Srivastava concluded that "the tropical influence of a proto-Gulf Stream extended over Orphan Knoll in latest Cretaceous time, but was considerably weaker closer to the western shore over the present Newfoundland shelf" and that "the expansion of North Atlantic waters, when the Labrador Sea started to open in latest Cretaceous time, is reflected in the impoverished, temperate assemblages on the Labrador Shelf and in Baffin Bay".

The change in the Upper Maastrichtian nannofossil assemblages and the subsequent disappearance of the nannoplankton flora in Indian Harbour M-52 is problematic. The substantial increase in frequency of *K. magnificus* and *A. cymbiformis* might be explained by an accelerated drop in water temperature, but, on the other hand, *N. frequens* declines sharply, *M. staurophora* becomes less abundant, and the frequency of *W. barnesae* rises slightly.

Shallowing is another possible explanation. The common occurrence of *K. magnificus* at Orphan Knoll (DSDP Site 111A) was interpreted by PerchNielsen (1972) as a nearshore effect. *L. cayeuxii* is also present at Site 111A (no frequency data available). In Indian Harbour M-52 *L. cayeuxii*, however, is absent.

Dissolution is not a likely reason for the assemblage changes. *K. magnificus* characterized by Roth (1973) as susceptible to solution occurs abundantly, and delicate forms like *L. quadratus* are present. Solution- resistant species such as *P. cretacea, E. turriseiffeli, M. staurophora, Biscutum* and *W. barnesae* (Thierstein, 1976) show inconsistent trends. Moreover, there is no notable difference in diversity between the two assemblages.

Gradstein and Berggren (1981) reported the occurrence of calcareous (plantonic as well as benthonic taxa) and agglutinated, flysch-type, foraminiferal assemblages in the uppermost Maastrichtian and lower Paleocene of Indian Harbour M-52. They could not determine, however, from the composite cuttings samples whether the agglutinated assemblages are associated with or alternate with the calcareous assemblages.

The disappearance of nannofossils in the uppermost Maastrichtian (-? lower Paleocene) of Indian Harbour M-52

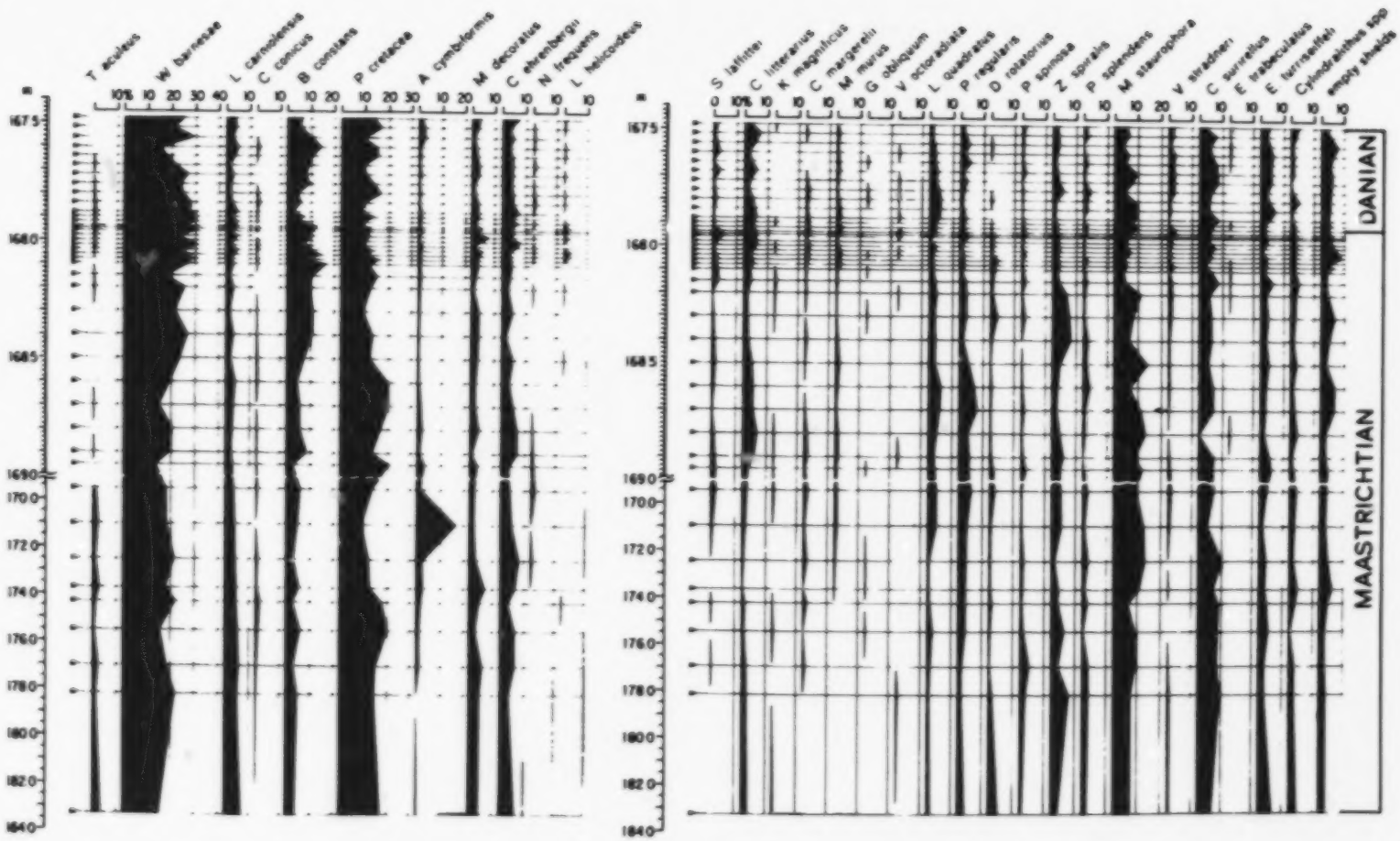

Figure 24. Relative abundances (in per cent) of nannofossil species in the Maastrichtian-Danian chalk of DSDP site 384 (J-anomaly ridge on the southern Grand Banks continental rise) (after Thierstein and Okada, 1979).

may well be correlative with the occurrence of the agglutinated foraminiferal assemblages. These flysch-type assemblages were considered by Gradstein and Berggren to reflect a paleoecological regime that involved "often relatively rapid, deposition of organic-rich, fine-grained clastics under somewhat restricted bottom water circulation conditions, leading to lower pH and low positive and/or negative Eh values at or just below the seafloor. Carbonate-poor provenance and low biogenic carbonate productivity enhanced these pH/Eh conditions." A minimum water depth of approximately 200 m was thought to be necessary to maintain the above conditions.

To conclude this section I will briefly discuss the depositional environment of the Wyandot chalk and some other chalk sequences in the North Atlantic region.

The Wyandot chalk (usually Upper Santonian-Upper Campanian/Lower Maastrichtian) was largely deposited under relatively warm water conditions (low M/W values), but the upper part may have accumulated under cooler water conditions (M/W reaches 1.0 in *Q. trifidum* Zone). The high concentrations of *L. cayeuxii* in the lower part of the chalk on the Scotian Shelf suggest a relatively nearshore environment. The significant decline of *L. cayeuxii* after the Middle Campanian may indicate deposition in 'deeper' waters. In Adolphus D-50 (northern Grand Banks) the chalk sedimentation in the Late Santonian-Middle Campanian interval took place farther from shore than on the Scotian Shelf (low scores of *L. cayeuxii*). The modest relative abundance peak of *L. cayeuxii* in the *Q. trifidum* Zone may reflect temporarily shallower water conditions in the vicinity of Adolphus D-50. For the Wyandot chalk accumulation rates have been calculated of 1 to 1.5 cm/ka on the Scotian Shelf and of 1.5 to 2 cm/ka in the vicinity of Adolphus D-50.

As pointed out earlier, the Maastrichtian chalk at DSDP Site 384, on the southern Grand Banks continental rise, was deposited under warm water conditions. The virtual absence of *L. cayeuxii* (rare occurrence in one sample; Okada and Thierstein, 1979) indicates a deep water environment (far from shore). A paleodepth close to 3 km has been calculated (backtracking method) by Thierstein and Okada (1979) for the Maastrichtian at Site 384. The accumulation rates vary from 0.6 to 2.0 cm/ka (Tucholke et al., 1979).

The Maastrichtian chalk at DSDP Site 111A (Orphan Knoll) was deposited under relatively warm water conditions in an outer neritic to upper bathyal environment (150 to 500 m) (Laughton et al., 1972, Chapter 3). The nannoplankton flora does contain *L. cayeuxii* (Perch-Nielsen, 1972), but no information is available about its frequency. The accumulation rate is about 0.3 cm/ka (Laughton et al., 1972).

The species frequency distribution in the (Lower) Maastrichtian chalk of the Hvidskud secton at Mons Klint, Denmark (see Fig. 25, after Surlyk and Birkelund, 1977) shows high percentages for *M. staurophora* and low values for *W. barnesae* (M/W ratio far above 1.0), and very high scores for *K. magnificus*, *A. cymbiformis* and *L. cayeuxii*.

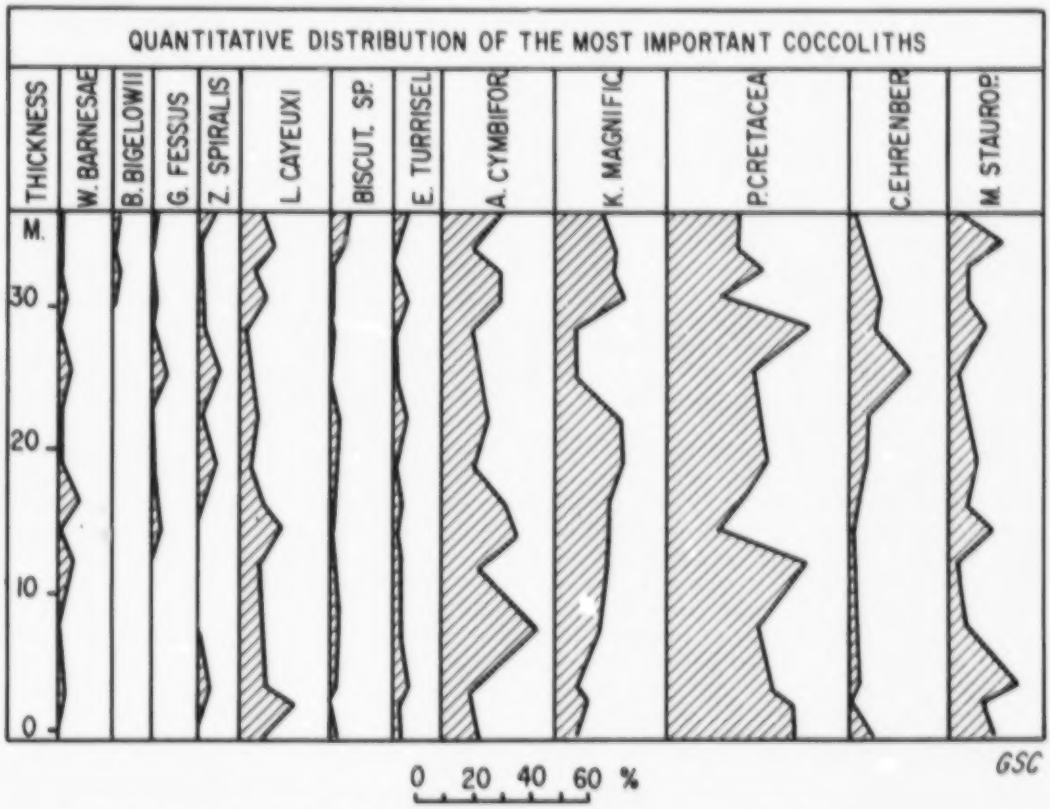

Figure 25. Relative abundances (in per cent) of the most important nannofossil species in the Mid-Lower Maastrichtian chalk of the Hvidskud section at Mons Klint (Denmark) (after Surlyk and Birkelund, 1977).

This frequency pattern reflects relatively cold water and nearshore conditions.

The Maastrichtian chalk of northwest Europe was described by Hakansson et al. (1974) as a pelagic shelf sediment, deposited in moderately shallow water no deeper than 250 m, but generally below the euphotic zone. The bathymetric interpretation is based on a variety of benthonic faunas. A remarkably high average accumulation rate of 15 cm/ka for the Danish chalk was given by Hakansson et al. (1974).

From the above comparisons it becomes clear that chalk sedimentation in the Latest Cretaceous took place under greatly varying water temperature, depth conditions, and accumulation rates. Factors governing chalk deposition may have been organic productivity, starvation of clastic sediment supply, and hydrodynamic conditions.

The relative frequency of *L. cayeuxii* in the lower part of the Wyandot chalk is comparable with that in the chalk of Mons Klint. If we may take the relative abundance of *L. cayeuxii* as a standard, then a depositional depth of approximately 150 to 200 m can be inferred for the lower part of the chalk on the Scotian Shelf. The 'deeper' depositional environment envisaged for the chalk in Adolphus D-50 and the upper part of the chalk on the Scotian Shelf is difficult to delineate. It may be upper bathyal.

Albian-Santonian

In this section I will briefly consider the distribution patterns of some species and possible depositional environments in the Mid-Albian-Santonian interval. No frequency counts were made for this interval, only rough estimates of species abundances ('rare', 'few', 'common', and 'abundant'). Throughout the mid-Albian-Santonian *Watznaueria barnesae* is the dominant species, which suggests relatively warm water conditions.

In nearly all of the studied wells on the Scotian Shelf the Albian- Lower Cenomanian comprises sandy sediments (Logan Canyon Formation) lacking nannofossils, presumably deposited in a (very) nearshore environment unfavourable for nannoplankton. A shaly interval in Triumph P-50 (Sable Member; Upper Albian) yielded nannofossil assemblages with common *Nannoconus* spp. (mostly *N. truitti*), indicative of a neritic environment.

In Adolphus D-50 (northern Grand Banks) the samples from the basal 1000 feet of the well either contain poor nannofossil assemblages (Middle- Upper Albian) or are barren. Subsequent rich nannoplankton floras of latest Albian-earliest Cenomanian age, with common nannoconids and *Braarudosphaera africana*, indicate the establishment of an open marine, neritic environment.

On the Scotian Shelf nannofossils are ubiquitous from the Upper Cenomanian-Lower Turonian onwards. The common occurrence of *Lithastrinus floralis* in the Cenomanian-Lower Santonian, both on the Scotian Shelf and northern Grand Banks, suggests more or less neritic conditions. Nannoconids are found occasionally, but are only common in the mid-Turonian of Wyandot E-53, the most nearshore of the wells studied. *Braarudosphaera bigelowii* is generally present, but usually in small numbers. It seems to be more common in Wyandot E-53 and MicMac H-86.

Marthasterites furcatus and *Lithastrinus grilli*, generally found in rather small numbers in the studied area, show distinct frequency peaks (common to abundant) in the Coniacian (-Lower Santonian) in Wyandot E-53, MicMac H-86, Missisauga H-54, and Mohawk B-93. *L. grilli* is most abundant in the Coniacian-Lower Santonian in Missisauga H-54 (3000 and 3655 feet) and in the Coniacian of Wyandot E-53 (1650 feet), *M. furcatus* in the Coniacian in Mohawk B-93 (2700 feet), and in the Coniacian in Wyandot E-53 (1650 feet). *L. grilli* is also common in the Lower Turonian in Wyandot E-53.

In the other studied wells these two species may occur in slightly higher numbers in the Coniacian-Lower Santonian than in other intervals within their range, but they are never common. Wyandot E-53, MicMac H-86, Missisauga H-54, and Mohawk B-93 are the four wells nearest to the present shoreline. Although *M. furcatus* and *L. grilli* are cosmopolitan, their abundance peaks in the wells most nearshore suggest a certain hemipelagic gradient in their distribution pattern.

On the Scotian Shelf *Lucianorhabdus cayeuxii* is rare and sporadic in the Coniacian-Lower Santonian, but becomes more abundant towards the end of the Santonian, especially in the Wyandot chalk. In Adolphus D-50 (northern Grand Banks) *L. cayeuxii* occurs regularly and sometimes is common in the Coniacian-Lower Santonian, but virtually disappears from the record in the Upper Santonian, showing up again in the Campanian.

The increase of *L. cayeuxii* at the top of the Santonian (upper part *Rucinolithus hayii* zone) on the Scotian Shelf may indicate a shift towards a more nearshore depositional environment. The distribution pattern of *L. cayeuxii* in Adolphus D-50 suggests deposition in an environment farther offshore (deeper) during the Late Santonian (relative to the Late Santonian on the Scotian Shelf and to the Coniacian-Early Santonian in Adolphus D-50). In the Campanian sedimentation in Adolphus D-50 may have taken place in somewhat shallower (more nearshore) waters, but presumably still outside the neritic zone (see previous section).

Diversity

The nannoplankton diversity on the Scotian Shelf, the Grand Banks, the Labrador Shelf and in the El Kef section in Tunisia, is shown graphically in Figure 26. The Scotian Shelf curve is the average for five wells, the curve of the northern Grand Banks is from Adolphus D-50 and that for the Labrador Shelf is from Indian Harbour M-52. Data for the El Kef curve are from Verbeek (1977). The diversity curves are based on the average number of species identified in the samples within each zone. They do not represent the total number of species recognized in a zone. It is emphasized that the curves presented give only an indication of the diversity. The number of species recognized in a sample depends not only on the diversity of the thanatocoenosis (which may differ from the biocoenosis), but also on factors such as the time spent examining it, the preservation of the nannofossils, one's species concept, and reworking and contamination.

The three curves in Figure 26 show roughly the same trend. The relative small number of species recognized in the Campanian on the Canadian Atlantic margin is probably due

to the often poor preservation of the nannofossils in the Wyandot chalk (secondary calcite overgrowth). The more irregular shape of the Scotian Shelf and Adolphus D-50 curves compared to the El Kef curve may reflect a less stable depositional environment. Sharp deflections occur in the Adolphus D-50 and El Kef curves in the Lower Turonian. A similar, albeit more explicit, diversity minimum was also observed by Wonders (1980) in the planktonic foraminiferal faunas of the western Mediterranean (see Fig. 27). Wonders suggested a relation between this diversity low and an oceanic oxygen minimum.

The relatively low average diversity in the Upper Turonian on the Scotian Shelf is caused by very low numbers of species in Wyandot E-53 and Triumph P-50, possibly reflecting fluctuating environmental conditions on the Scotian Shelf.

In the Upper Maastrichtian the decreasing number of species from the Scotian Shelf to the northern Grand Banks to the Labrador Shelf may reflect a temperature gradient.

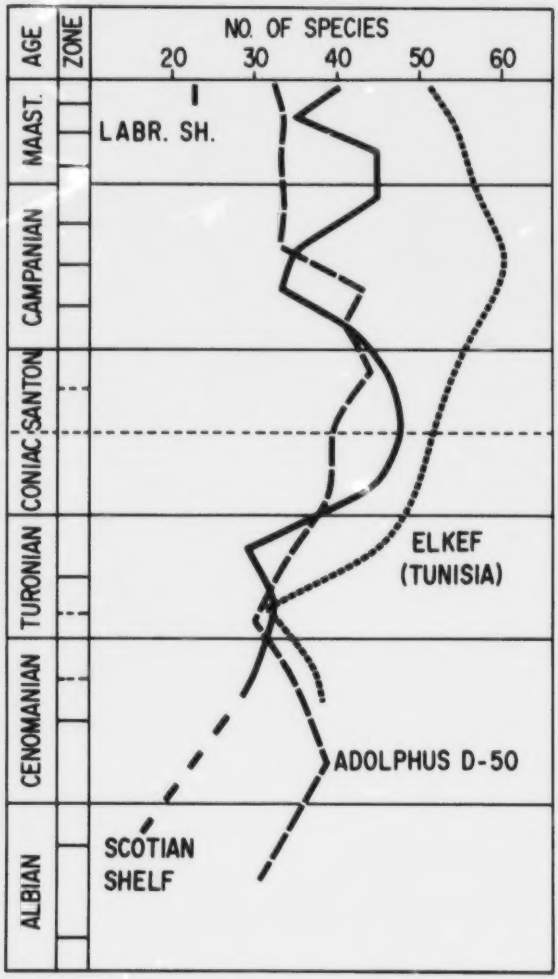

Figure 26. Diversity curves from Labrador Shelf (Indian Harbour M-52), northern Grand Banks (Adolphus D-50), and Scotian Shelf (average of 5 wells) are compared with that from the E1 Kef section in Tunisia (data from Verbeek, 1977).

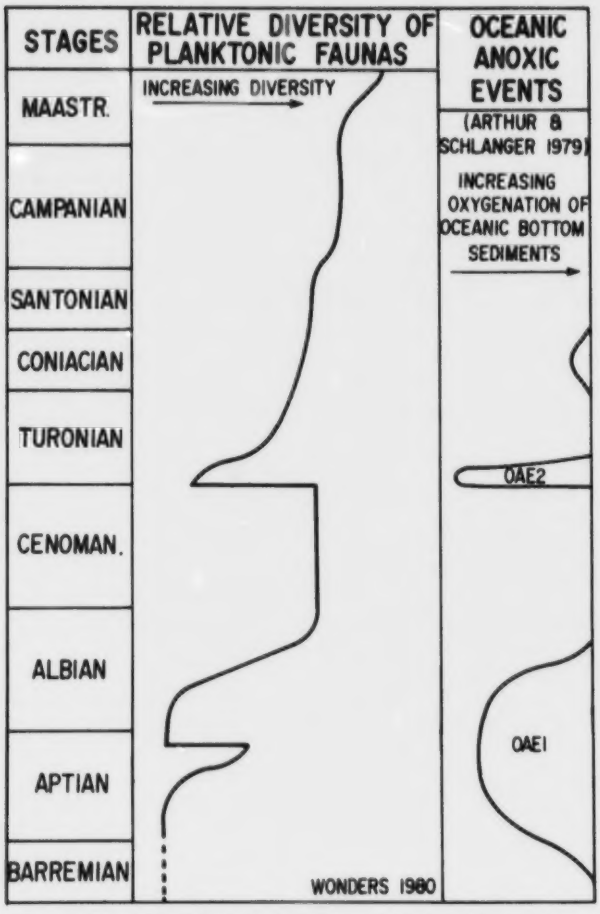

Figure 27. Correlation between the relative diversity of planktonic foraminiferal faunas in the Western Mediterranean and oceanic anoxic events (Figure after Wonders, 1980).

TAXONOMY

In the present study a generally broad taxonomic concept has been adopted, based on morphological features detectable with a light microscope. A list of identified taxa, with author citations, is given in the appendix.

Most of the stratigraphically and/or paleoecologically important species, discussed in this paper are illustrated in Plates 1 to 6. Some taxa are commented on below.

Arkhangelskiella cymbiformis Vekshina 1959
(Plate 4, figure 4)

Arkhangelskiella cymbiformis Vekshina, 1959, p. 66, Pl. 2, fig. 3 a,b; Bramlette and Martini, 1964, p. 297, Pl. 1, fig. 3-9; Gartner, 1968, p. 38, Pl. 1, fig. 1-6, Pl. 4, fig. 1-4, Pl. 6, fig. 1a-c, Pl. 27, fig. 2; Bukry, 1969, p. 21, Pl. 1, fig. 1-3; Manivit, 1971, p. 103, Pl. 1, fig. 6-11; Risatti, 1973, p. 25, Pl. 1, fig. 22,23.

Remarks: Referred to this species are forms of *Arkhangelskiella* with 5 or less perforations in each quadrant of the central area, situated along the sutures. The sutures are parallel to the axes of the elliptical disc.

Arkhangelskiella specillata Vekshina 1959
(Plate 2, figure 4)

Arkhangelskiella specillata Vekshina 1959, p. 67, Pl. 2, fig. 5; Gartner,1968, p. 39, Pl. 8, fig. 6-7, Pl. 11, fig. 4a-c; Manivit, 1971, p. 104, Pl. 1, fig. 16-17; Risatti, 1973, p. 25, Pl. 1, fig. 16-17; Wise and Wind,1977, Pl. 29, fig. 4-6.

Arkhangelskiella specillata ethmopora Bukry 1969, p. 21, Pl. 1, fig. 4-7

Arkhangelskiella ethmopora Bukry, Manivit 1971, p. 103, Pl. 1, fig. 12-14

Remarks: *A. specillata* differs from *A. cymbiformis* in having a narrower margin, one oblique suture (the short one), and a larger number of perforations, some of which are situated along the edge of the central plate.

Broinsonia ex gr. *furtiva-lacunosa*
(Plate 5, figures 9-12)

Arkhangelskiella cymbiformis Vekshina, Stover, 1966, partim, p. 137, Pl. 1, fig. 18, non Pl. 1, fig. 17

Broinsonia furtiva Bukry, 1969, p. 22, Pl. 2, fig. 7,8; Thierstein, 1974, p. 637, Pl. 10, fig. 7-14, Pl. 11, fig. 1-8; Verbeek, 1977, p. 74, Pl. 2, fig. 6,7

Broinsonia parca (Stradner) Bukry, 1969, partim, p. 23, Pl. 3, fig. 7, non Pl. 3, fig. 3-6, 8-10

Broinsonis lacunosa Forchheimer, 1972, p. 25, Pl. 2, fig. 1; Verbeek, 1977, p. 74, Pl. 2, fig. 8-9

Remarks: Included in this group are representatives of *Broinsonia* with a perforated central area, not belonging to *B. parca*. *B. parca* has a relatively smaller central area, a more distinct peripheral rim, and a more prominent ridge around the central area at the distal side. *B. furtiva* Bukry 1969 and *B. lacunosa* Forchheimer 1972 belong to this group, but these species could not consistently be separated. The shape, distribution and number of perforations, diagnostic features of these two species, could not always be determined with the lightmicroscope. In his original description of *B. furtiva*, Bukry (1969) made mention of a central area composed of a narrow axial cross and (in each quadrant) 4 large roughly triangular perforations, which are largely closed by one thick bar and several transverse bars. Forchheimer (1972) originally diagnosed *B. lacunosa* as a species of *Broinsonia* with a large central area divided by a cross, consisting of double rows of elements, into four quadrants, each with six perforations aligned with the crossbars.

The lowest occurrence of *B. lacunosa* has been employed as a marker for the base of the Santonian by Verbeek (1976, 1977) and subsequently been incorporated in the zonation of Roth (1978). Verbeek (1976, 1977) described *B. lacunosa* as a form with a narrow margin and a large central area with indistinct sutures (no cross bars) and distinct perforations (2-7 per quadrant). He considered *B. lacunosa* as the ancestor of *B. parca*. *B. furtiva* was characterized by Verbeek as a form with 4 prominent bars and large and irregular perforations.

In my opinion, however, this species concept is incorrect; the holotype of *B. lacunosa* (Forchheimer, 1972) has distinct cross bars.

Moreover, Verbeek's synonony lists for *B. lacunosa* and *B. furtiva* are not entirely consistent with his species concept.

Eiffellithus eximius (Stover 1966) Perch-Nielsen 1968
(Plate 2, figures 1-2)

Clinorhabdus eximius Stover, 1966, p. 138, Pl. 2, fig. 15-16, Pl. 8, fig. 15

Eiffellithus turriseiffeli (Deflandre, 1954) Reinhardt, 1965, Gartner, 1968, partim, p. 26, Pl. 16, fig. 1-(?)2; Pl. 17, fig. 3; Pl. 18, fig. 9(?)-10; Pl. 19., fig. 1-2; Pl. 22, fig. 4(?); Pl. 23, fig. 8-11; Pl. 24, fig. 1(?)-2; Pl. 26, fig. 3-4; non Pl. 2, fig. 22-23; Pl. 3, fig. 13; Pl. 5, fig. 19; Pl. 7, fig. 5; Pl. 9, fig. 6-10; Pl. 13, fig. 1-2; Pl. 18, fig. 11; Pl. 13, fig. 7; Pl. 25, fig. 15-16

Eiffellithus eximius (Stover) Perch-Nielsen, 1968, p. 30, Pl. 3, fig. 8-10; Verbeek, 1977, p. 88, Pl. 5, fig. 6-7

Eiffellithus augustus Bukry, 1969, p. 51, Pl. 28, fig. 10-12, Pl. 29, fig. 1

Kamptnerius magnificus Deflandre 1959
(Plate 4, figures 5,6)

Kamptnerius magnificus Deflandre, 1959, p. 135, Pl. 1, fig. 1-4; Bramlette and Martini, 1964, p. 301, Pl. 2, fig. 3; Stover, 1966, p. 144, Pl. 4, fig. 28-30; Manivit, 1971, p. 107, Pl. 14, fig. 10-14, Pl. 20, fig. 11; Roth, 1973, p. 718, Pl. 23, fig. 1-2; Thierstein, 1974, p. 640, Pl. 8, fig. 1-9; Pl. 9, fig. 1-11; Thierstein, 1976, p. 351, Pl. 1, fig. 1-2, Pl. 4, fig. 38-39; Wise and Wind, 1977, Pl. 45, fig. 1-6.

Kamptnerius punctatus Stradner, 1963, p. 11, Pl. 2, fig. 3; Bukry, 1969, p. 26, Pl. 6, fig. 4-5; Manivit, 1971, p. 108, Pl. 14, fig. 8-9; Forchheimer, 1972, p. 30, Pl. 4, fig. 1-3; Pl. 5, fig. 5-6

Kamptnerius ? minimus Reinhardt, 1964, p. 752, Pl. 1, fig. 5

Kamptnerius ? tabulatus Perch-Nielsen, 1968, p. 42, Pl. 6, fig. 4

Kamptnerius magnificus magnificus (Deflandre) Bukry, 1969, p. 25, Pl. 5, fig. 7-9

Kamptnerius magnificus sculptus Bukry, 1969, p. 25, Pl. 5, fig. 10-12

Kamptnerius percevalii Bukry, 1969, p. 25, Pl. 6, fig. 1-3

Kamptnerius pseudopunctatus Cepek, 1970, p. 242, Pl. 24, fig. 7-9; Roth, 1973, p. 718, Pl. 23, fig. 3-5

Kamptnerius pertusus Forchheimer, 1972, p. 30, Pl. 5, fig. 1-4

Remarks: *Kamptnerius* is here considered to be monospecific. Thierstein (1974,1976) has demonstrated that morphological variations in the central area of *Kamptnerius*, on the strength of which several species have been distinguished, can be attributed to differences in preservation.

Lithraphidites sp. aff. *L. quadratus*
(Plate 6, figures 1-3)

A variety of forms of *Lithraphidites* was found in the Upper Cenomanian, especially in Primrose A-41 and Sachem D-76. Some of these have very wide blades and closely resemble the Maastrichtian *L. quadratus*.

There seem to have been two relatively short periods of radiation of *Lithraphidites*:

(1) Cenomanian with *L. alatus*, *L. acutum* and *L.* aff. *quadratus* and other variants.
(2) Maastrichtian, with *L. praequadratus*, *L. quadratus* and variants such as *L. grossopectinatus*.

Both radiations may have originated from *L. carniolensis*, a simple form, which ranges throughout the Cretaceous. Roth (1978) demonstrated an evolutionary lineage from *L. carniolensis* to *L. praequadratus* to *L. quadratus*.

Lucianorhabdus sp. 2

Tentatively named *Lucianorhabdus* sp. 2 are *Lucianorhabdus*-like forms that have a short, tapering stem with a terminal plug and a thick basal plate. In crosspolarized light the sutures between the stem and the basal plate show a characteristically curved extinction line (see Plate 6, fig. 9-20).

Lucianorhabdus sp. 2 ranges from Cenomanian to Coniacian (see Fig. 6).

Micula concava (Stradner 1960) Bukry 1969
(Plate 2, figures 8-9)

Nannotetraster concavus Stradner in Martini and Stradner 1960, p. 269, Text-fig. 18

Micula staurophora (Gardet, 1955) Stradner, 1963, partim, Pl. 4, fig. 12, 12 b-c, non Pl. 4, fig. 12a

Micula decussata Vekshina, Gartner, 1968, partim, p. 47, Pl. 2, fig. 6-7; Pl. 9, fig. 19-20; Pl. 14, fig. 14, non Pl. 2, fig. 5,8; Pl. 4, fig. 18, Pl. 9, fig. 18, Pl. 14, fig. 13; Pl. 18, fig. 7; Pl. 20, fig. 15

Micula decussata concava (Stradner) Bukry, 1969, p. 67, Pl. 40, fig. 7-8

Micula concava (Stradner) Bukry, Verbeek, 1977, p. 119, Pl. 11, fig. 11

Remarks: *M. concava* has processes at the corners of the cube and more concave edges than *M. decussata*. In the counting procedures and paleoecological analysis the term *Micula* "*staurophora*" has been informally used to embrace *M. concava* and *M. decussata*.

Quadrum gartneri Prins and Perch-Nielsen 1977
(Plate 1, figure 10-11)

Tetralithus gothicus Deflandre, Gartner, 1968, p. 42, Pl. 24, fig. 4

Micula staurophora (Gardet, 1955) Stradner, Thierstein, 1974, partim, Pl. 12, fig. 4-8; non Pl. 12, fig. 1-3, 9-11

Tetralithus descriptus Martini, 1961, Risatti, 1973, p. 31, Pl. 4, fig. 16-17

Tetralithus pyramidus Gardet, 1955, Verbeek, 1976b, Pl. 1, fig. 4(?),6

Quadrum gartneri Prins and Perch-Nielsen in Manivit et al. 1977, p. 177, Pl. 1, fig. 9-10; Verbeek, 1977, p. 121, Pl. 12, fig. 6-8

Remarks: To this species belong cube shaped forms consisting of one or two layers of four calcite elements, separated by suture, perpendicular to the margin.

A discussion about the relations between the genera Quadrum, Tetralithus, and Micula can be found in Manivit et al. (1977).

Quadrum gothicum (Deflandre, 1959)
Prins and Perch-Nielsen 1977
(Plate 3, figure 4)

Tetralithus gothicus Deflandre, 1959, p. 138, Pl. 3, fig. 25; Martini, 1976, Pl. 12, fig. 3-4; Thierstein, 1976, p. 351, Pl. 5, fig. 24-25; Wise and Wind, 1977, Pl. 50, fig. 3

Tetralithus nitidus Martini, 1961, p. 4, Pl. 1, fig. 5, Pl. 4, fig. 41; Gartner, 1968, partim p. 42, Pl. 13, fig. 13, non Pl. 9, fig. 14; Pl. 13, fig. 4; Sissingh, 1977, p. 61

Tetralithus pyramidus Gardet, 1955, Manivit, 1971, partim, p. 145, Pl. 25, fig. 1-2,8; non Pl. 25, fig. 6-7

Quadrum gothicum (Deflandre) Prins and Perch-Nielsen in Manivit et al. 1977, p. 178; Verbeek, 1977, p. 122, Pl. 12, fig. 10

Quadrum nitidum (Martini) Prins and Perch-Nielsen in Manivit et al. 1977, p. 178, Verbeek, 1977, p. 122, Pl. 12, fig. 9

Remarks: Referred to this species are forms of *Quadrum* with four more or less elongated elements.

Reinhardtites anthophorus (Deflandre 1959)
Perch-Nielsen 1968, emend.
Prins and Sissingh, 1977
(Plate 2, figure 5-6)

Rhabdolithus anthophorus Deflandre, 1959, p. 137, Pl. 1, fig. 21-22; Stradner, 1963, Pl. 5, fig. 4, 4a-b

Cretarhabdus? anthophorus (Deflandre) Bramlette and Martini, 1964, p. 299, Pl. 3, fig. 1-4

Reinhardtites anthophorus (Deflandre) Perch-Nielsen, 1968, partim, p. 38, Pl. 5, fig. 1,5,6; non Text fig. 13-14; Pl. 5, fig. 2-4, 7-8; Manivit, 1971, partim, p. 89, Pl. 20, fig. 9-10, 13-14; non Pl. 20, fig. 12; Roth, 1973, Pl. 22, fig. 4

Reinhardtites anthophorus (Deflandre) Perch-Nielsen emend. Prins and Sissingh in Sissingh, 1977, p. 61, Pl. 1, fig. 5 a-d

Remarks: The species concept of Sissingh (1977) is followed: placed in *R. anthophorus* are forms with moderately large openings, surrounded by a "blocky" or "pitted" plate lining; forms with small openings, a broad and smooth plate lining, and a short bridge structure are assigned to *R. levis* Prins and Sissingh 1977. Transitional types between *R. anthophorus* and *R. levis*, resembling *R.* aff. *anthophorus* of Sissingh (1977, Pl. 1, fig. 4), also occur.

Reinhardtites levis Prins and Sissingh 1977
(Plate 3, figures 5-6)

Reinhardtites anthophorus (Deflandre, 1959) Perch-Nielsen, 1968, partim, p. 38, Text fig. 13-14; Pl. 5, fig. 2-4, 7-8, non Pl. 5, fig. 1,5,6

Zygodiscus sp. Risatti, 1973, Pl. 10, fig. 18-19

Reinhardtites levis Prins and Sissingh in Sissingh, 1977, p. 61, Pl. 1, fig. 1-3

Remarks: See remarks under *R. anthophorus*

Rhagodiscus achylostaurion (Hill, 1976) n. comb.

Parhabdolithus achylostaurion Hill, 1976, p. 145, Pl. 9, fig. 24-29

Remarks: This species has a closed (perforated) central area and lacks a bridge structure; therefore it belongs to the genus *Rhagodiscus* Reinhardt, 1967 rather than to *Parhabdolithus* Deflandre, 1952.

"*Tetralithus*" *copulatus* Deflandre, 1959
(Plate 5, figures 1-8)

Tetralithus copulatus Deflandre, 1959, p. 138, Pl. 3, fig. 19-24; Wind, 1975, p. 265-268, fig. 1

Remarks: Sporadic specimens of this distinctive, but very rarely reported, species were found in the *Quadrum trifidum* Zone in Adolphus D-50, MicMac H-86, Missisauga H-54 and Primrose A-41. They all have a very large cross-like distal structure, which almost completely obscures the basal shield construction. They closely resemble the morphotypes illustrated in Figure 1 m-p of Wind (1975).

The study by Wind (1975) revealed that the basal shield construction of "*T.*" *copulatus* is composed of two monocyclic shields, each comprising 18-20 elements. The elements in the proximal shield are radial and nonimbricate, those in the distal shield are clockwise inclined and sinistrally imbricate. Wind observed in the Upper Campanian-Maastrichtian of DSDP sites 217 and 249 (Indian Ocean) a wide range in the dimensions of the central structure of *T. copulatus*.

As pointed out by Wind (1975), the presence of coccolith shields excludes this species from the genus *Tetralithus*. Wind suggested this form be assigned to the genus *Markalius* or a new genus be erected.

Vekshinella gausorhethium (Hill 1976) n. comb.

Vagalapilla gausorhethium Hill, 1976, p. 157, Pl. 3, fig. 25-30

Remarks: *Vagalapilla* Bukry 1969 is considered a junior synonym of *Vekshinella* Loeblich and Tappan 1963 (see discussion in Wise and Wind, 1977, p. 307; and Verbeek, 1977, p. 95). Characteristic for this species is the slightly sinusoid extinction pattern of the cross bars in cross polarized light.

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APPENDIX

List of identified Cretaceous species

Acuturris scotus (Risatti, 1973) Wind and Wise in Wise and Wind, 1977
Ahmuellerella octoradiata (Gorka, 1957) Reinhardt, 1966a
A. regularis (Gorka, 1957) Verbeek, 1977
Arkhangelskiella cymbiformis Vekshina, 1959 (Pl. 4, fig. 4)
A. specillata Vekshina, 1959 (Pl. 2, fig. 4)
Bidiscus ignotus (Gorka, 1957) Hoffmann, 1970
Biscutum constans (Gorka, 1957) Black, 1967
Braarudosphaera africana Stradner, 1961
B. bigelowii (Gran and Braarud, 1935) Deflandre, 1947
B. quinquecostata Hill, 1976
Broinsonia enormis (Shumenko, 1968) Manivit, 1971
B. ex gr. *furtiva-lacunosa* (Pl. 5, fig. 9-12)
B. gammation Hill, 1976
B. matalosa (Stover, 1966) Thierstein? sl.
B. parca (Stradner, 1963) Bukry, 1969 (Pl. 3, fig. 1-2)
B. cf. *stenostaurion* Hill, 1976
Ceratolithoides aculeus (Stradner, 1961) Prins and Sissingh in Sissingh, 1977 (Pl. 3, fig. 3)
C. kamptneri Bramlette and Martini, 1964
Chiastozygus amphipons (Bramlette and Martini, 1964) Gartner, 1968
C. litterarius (Gorka, 1957) Manivit, 1971
Corollithion achylosum (Stover, 1966) Thierstein, 1971
C. completum Perch-Nielsen, 1973 (Pl. 1, fig. 9)
C. cf. *ellipticum* Bukry, 1969
C. exiguum Stradner, 1961
C. geometricum (Gorka, 1957) Manivit, 1971
C. rhombicum (Stradner and Adamiker, 1966) Bukry, 1969
C. signum Stradner, 1963
Cretarhabdus conicus Bramlette and Martini, 1964
C. crenulatus Bramlette and Martini, 1964 emend. Thierstein, 1971
C. loriei Gartner, 1968
C. schizobrachiatus (Gartner, 1968) Bukry, 1969
C. surirellus (Deflandre in Deflandre and Fert, 1954) Reinhardt, 1970

Cribrocorona gallica (Stradner, 1963) Perch-Nielsen, 1973
Cribrosphaerella circula (Risatti, 1973) Verbeek, 1977
C. ehrenbergii (Arkhangelsky, 1912) Deflandre, 1952
C. pelta Gartner, 1968
Cruciellipsis chiastia (Worsley, 1971) Thierstein in Roth and Thierstein, 1972 (Pl. 1, fig. 5,6)
Cyclagelosphaera margereli Noël, 1965
C. perforata (Perch-Nielsen, 1973) Verbeek, 1977
C. rotaclypeata Bukry, 1969
Cylindralithus asymmetricus Bukry, 1969
C. biarcus Bukry, 1969
C. coronatus Bukry, 1969
C. duplex Perch-Nielsen, 1973
C. serratus Bramlette and Martini, 1964
Dodekapodorhabdus noelae Perch-Nielsen, 1968
Eiffellithus eximius (Stover, 1966) Perch-Nielsen, 1968 (Pl. 2, fig. 1,2)
E. cf. *gorkae* Reinhardt, 1965
E. parallelus Perch-Nielsen, 1973
E. trabeculatus (Gorka, 1957) Reinhardt and Gorka, 1967
E. turriseiffeli (Deflandre in Deflandre and Fert, 1954) Reinhardt, 1965 (Pl. 1, fig. 1-2)
Flabellites biforaminis Thierstein, 1973
Gartnerago aff. *nanum* Thierstein, 1974
G. obliquum (Stradner, 1963) Reinhardt, 1970 s.l.
G. striatum (Stradner, 1963) Forchheimer, 1972
G. zipperum Bukry, 1969
Heliorthus concinnus (Martini, 1961) Hay and Mohler, 1967
Kamptnerius magnificus Deflandre, 1959 s.l. (Pl. 4, fig. 5-6)
Lithastrinus floralis Stradner, 1962 (Pl. 2, fig. 10-11)
L. grilli Stradner, 1962 (Pl. 4, fig. 10-11)
L. aff. *moratus* Stover, 1966
Lithraphidites acutum Verbeek and Manivit in Manivit et al., 1977 (Pl. 1, fig. 4)
L. alatus Thierstein in Roth and Thierstein, 1972
L. carniolensis Deflandre, 1963 (Pl. 6, fig. 7-8)
L. praequadratus Roght, 1978
L. quadratus Bramlette and Martini, 1964 (Pl. 3, fig. 8-9; Pl. 6, fig. 5-6)
L. aff. *quadratus* Bramlette and Martini, 1964 (Pl. 6, fig. 1-3)
Lucianorhabdus arcuatus Forchheimer, 1972
L. cayeuxii Deflandre, 1959 (Pl. 4, fig. 7)
L. aff. *compactus* (Verbeek, 1976a) Prins and Sissingh in Sissingh, 1977
L. maleformis Reinhardt, 1966a (Pl. 1, fig. 12)
L. cf. *quadrifidus* Forchheimer, 1972
Lucianorhabdus sp. 2 (Pl. 6, fig. 9-10)
Manivitella pemmatoidea (Deflandre in Manivit, 1965) Thierstein, 1971
Markalius circumradiatus (Stover, 1966) Perch-Nielsen, 1968
Marthasterites furcatus Deflandre, 1959 s.l. (Pl. 2, fig. 3)
M. inconspicuus Deflandre, 1959
Microrhabdulus belgicus Hay and Towe, 1963
M. decoratus Deflandre, 1959
M. helicoideus Deflandre, 1959
M. stradneri Bramlette and Martini, 1964
Micula concava (Stradner in Martini and Stradner, 1960) Bukry, 1969 (Pl. 2, fig. 8-9)
M. decussata Vekshina, 1959 (Pl. 4, fig. 3)
M. cf. *murus* (Martini, 1961) Bukry, 1969
Munarinus marszaleki Risatti, 1973
Nannoconus cf. *elongatus* Brönnimann, 1975
N. multicadus Deflandre and Deflandre-Rigaud, 1960
N. truitti Brönnimann, 1955
Nephrolithus frequens Gorka, 1957 (Pl. 3, fig. 10-11)
Octopodorhabdus aff. *decussatus* (Manivit, 1961) Manivit, 1971
Parhabdolithus embergeri (Noël, 1959) Stradner, 1963
Phanulithus obscurus (Deflandre, 1959) Wind and Wise in Wise and Wind, 1977 (Pl. 4, fig. 8)
P. ovalis (Stradner, 1963) Wind and Wise in Wise and Wind, 1977 (Pl. 4, fig. 9)
Podorhabdus albianus Black, 1967 (Pl. 1, fig. 7-8)
P. coronadventis (Reinhardt, 1966a) Reinhardt, 1970
P. decorus (Deflandre in Deflandre and Fert, 1954) Thierstein in Roth and Thierstein, 1972)
P. dietzmanni (Reinhardt, 1965) Reinhardt, 1967
Prediscosphaera columnata (Stover, 1966) Manivit, 1971
P. cretacea (arkhangelsky, 1912) Gartner, 1968
P. spinosa (Bramlette and Martini, 1964) Gartner, 1968 s.l.
Prolapitella multicarinata Gartner, 1968
Quadrum gartneri Prins and Perch-Nielsen in Manivit, 1977 (Pl. 1, fig. 10-11)
Q. gothicum (Deflandre, 1959) Prins and Perch-Nielsen in Manivit, 1977 (Pl. 3, fig. 6)
Q. quadratum (Stradner, 1961) Verbeek, 1977
Q. trifidum (Stradner in Stradner and Papp, 1961) Prins and Perch-Nielsen in Manivit, 1977 (Pl. 3, fig. 7)
Reinhardtites anthophorus (Deflandre, 1959) Perch-Nielsen, 1968 emend. Prins and Sissingh in sissingh, 1977 (Pl. 2, fig. 5-6)
R. brooksii (Bukry, 1969) Verbeek, 1977
R. cf. *fenestratus* (Worsley, 1971) thierstein in Roth and Thierstein, 1972
R. levis Prins and Sissingh in Sissingh, 1977 (Pl. 3, fig. 5-6)
R. cf. *miniporus* (Reinhardt and Gorta, 1967) Verbeek, 1977
Rhagodiscus achylostaurion (Hill, 1976) n. comb.
R. angustus (Stradner, 1963) Reinhardt, 1971
R. asper (Stradner, 1963) Reinhardt, 1967
R. reniformis Perch-Nielsen, 1973
R. splendens (Deflandre, 1953) Verbeek, 1977
Rucinolithus hayii Stover, 1966 (Pl. 2, fig. 7)
Scapholithus fossilis Deflandre in Deflandre and Fert, 1954
Sollasites horticus (Stradner, Adamiker and Maresch in Stradner and Adamiker, 1966), Cepek and Hay, 1969a
Stephanolithion laffittei Noël, 1957
"Tetralithus" copulatus Deflandre, 1959 (Pl. 5, fig. 1-8)
Thoracosphaera cf. *operculata* Bramlette and Martini, 1964
Tranolithus exiguus Stover, 1966
T. gabalus Stover, 1966
T. aff. *manifestus* Stover, 1966
T. orionatus (Reinhardt, 1966a) Reinhardt, 1966b
T. phacelosus Stover, 1966
Vekshinella aachena (Bukry, 1969) Wind and Wise in Wise and Wind, 1977
V. bochotnicae (Gorka, 1957) Verbeek, 1977
V. crux (Deflandre and Fert, 1954) Risatti, 1973
V. gausorhethium (Hill, 1976) n. comb.
Watznaueria barnesae (Black and Black and Barnes, 1959) Perch-Nielsen, 1968 (Pl. 4, fig. 1-2)
W. biporta Bukry, 1969
W. britannica (Stradner, 1963) Reinhardt, 1964 (Pl. 1, fig. 3)
W. ovata Bukry, 1969
Zygodiscus acanthus (Reinhardt, 1965) Reinhardt, 1966a
Z.? biperforatus Gartner, 1968
Z. diplogrammus (Deflandre in Deflandre and Fert, 1954) Gartner, 1968
Z. elegans Gartner, 1968 emend. Bukry, 1969
Z. minimus Bukry, 1969
Z. pseudanthophorus Bramlette and Martini, 1964
Z. sigmoides Bramlette and Sullivan, 1961
Z. spiralis Bramlette and Martini, 1964
Z. theta (Black in Black and Barnes, 1959) Bukry, 1969
Z. xenotus (Stover, 1966) Hill, 1976

PLATE 1

All figures x3200

Figures 1-2 *Eiffellithus turriseiffeli* (Deflandre, 1954) Reinhardt, 1965, Onondaga E-84, 3977 feet (*N. frequens* Zone).
1: Cross-polarized light
2: Transmitted light, same specimen as Figure 1

Figure 3 *Watznaueria britannica* (Stradner, 1963) Reinhardt 1964 Adolphus D-50, 10 900 feet (*E. turriseiffeli* Zone, lower part). Cross-polarized light

Figure 4 *Lithraphidites acutum* Verbeek and Manivit, 1977 Missisauga H-54, 4100 feet (*L. acutum* Zone, lower part). Cross-polarized light

Figures 5-6 *Cruciellipsis chiastia* (Worsley, 1971) Thierstein, 1972
5: Primrose A-41, 5322 feet (*L. acutum* Zone, lower part). Cross-polarized light
6: Missisauga H-54, 4100 feet (*L. acutum* Zone, lower part). Cross-polarized light

Figures 7-8 *Podorhabdus albianus* Black, 1967, Primrose A-41, 5330 feet (*L. acutum* zone, lower part)
7: Cross-polarized light
8: Transmitted light, same specimen as Figure 7

Figure 9 *Corollithion completum* Perch-Nielsen, 1973 Adolphus D-50, 10 210 feet (*L. acutum* Zone, upper part). Cross-polarized light

Figures 10-11 *Quadrum gartneri* Prins and Perch-Nielsen, 1977 Primrose A-41, 5313.5 feet (Coniacian)
10: Cross-polarized light
11: Transmitted light, some specimen as Figure 10

Figure 12 *Lucianorhabdus maleformis* Reinhardt, 1966 Mohawk B-93, 2400 feet (Coniacian-Santonian) Cross-polarized light

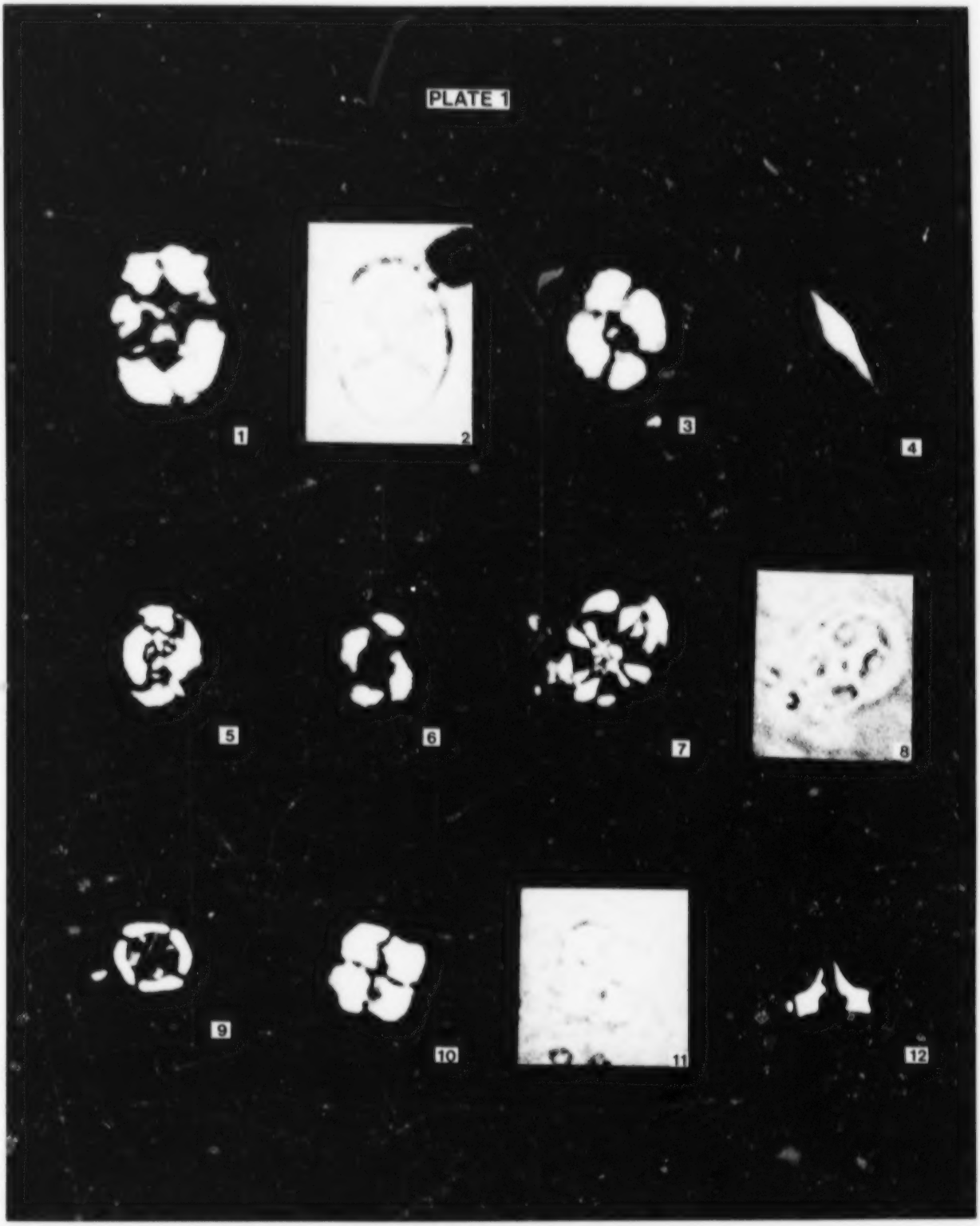
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PLATE 2

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Figures 1-2 *Eiffellithus eximius* (Stover, 1966) Perch-Nielsen, 1968 Primrose A-41, 5313.5 feet (Coniacian)
1: Cross-polarized light
2: Transmitted light, same specimen as Figure 1

Figure 3 *Marthasterites furcatus* Deflandre, 1959 Mohawk b-93, 2500 feet (Coniacian) Transmitted light

Figure 4 *Arkhangelskiella specillata* Vekshina, 1959 Sachem D-76, 5790 feet (cuttings fragment) Cross-polarized light

Figures 5-6 *Reinhardtites anthophorus* (Deflandre, 1959) Perch-Nielsen, 1968 Mohawk B-93, 2200 feet (Santonian)
5: Cross-polarized light
6: Transmitted light, same specimen as Figure 5

Figure 7 *Rucinolithus hayii* Stover, 1966 Wyandot E-53, 1360 feet (*R. hayii* Zone) Cross-polarized light

Figures 8-9 *Micula concava* (Stradner, 1960) Bukry, 1969 Mic Mac H-86, 2284 feet (*Q. trifidum* Zone)
8: Cross-polarized light
9: Transmitted light, same specimen as Figure 8

Figures 10-11 *Lithastrinus floralis* Stradner, 1962 Mohawk B-93, 2500 feet (Coniacian)
10: Cross-polarized light
11: Transmitted light, same specimen as Figure 10

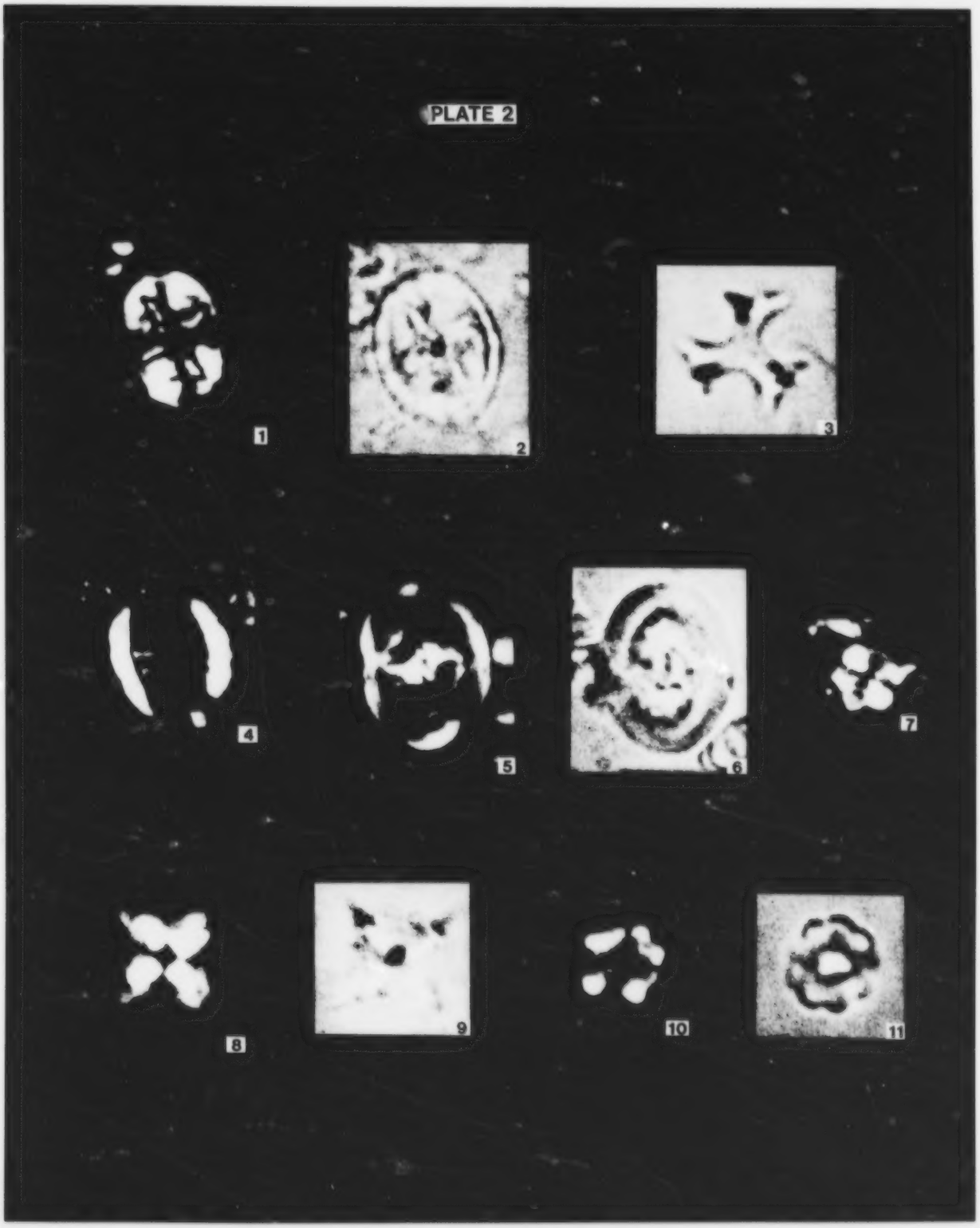
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PLATE 3

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Figures 1-2 *Broinsonia parca* (Stradner, 1963) Bukry, 1969 Mic Mac H-86, 2284 feet (*Q. trifidum* Zone)
1: Cross-polarized light
2: Transmitted light, same specimen as Figure 1

Figure 3 *Ceratolithoides aculeus* (Stradner, 1961) Prins and Sissingh, Sachem D-76,5790 feet (cuttings fragment) Cross-polarized light

Figure 4 *Quadrum gothicum* (Deflandre, 1959) Prins and Perch-Nielsen, 1977 Mic Mac H-86, 2284 feet (*Q. trifidum* Zone) Cross-polarized light

Figures 5-6 *Reinhardtites levis* Prins and Sissingh, 1977 Mic Mac H-86 2284 feet (*Q. trifidum* Zone)
5: Cross-polarized light
6: Transmitted light, same specimen as Figure 5

Figure 7 *Quadrum trifidum* (Stradner, 1961) Prins and Perch-Nielsen, 1977 Mic Mac H-86, 2284 feet (*Q. trifidum* Zone) Cross-polarized light

Figures 8-9 *Lithraphidites quadratus* Bramlette and Martini, 1964 Onondaga E-84, 3977 feet (*N. frequens* Zone)
8: Cross-polarized light
9: Transmitted light, same specimen as Figure 8

Figures 10-11 *Nephrolithus frequens* Gorka, 1957 Onondaga E-84, 3977 feet (*N. frequens* Zone)
10: Cross-polarized light
11: Transmitted light, same specimen as Figure 10

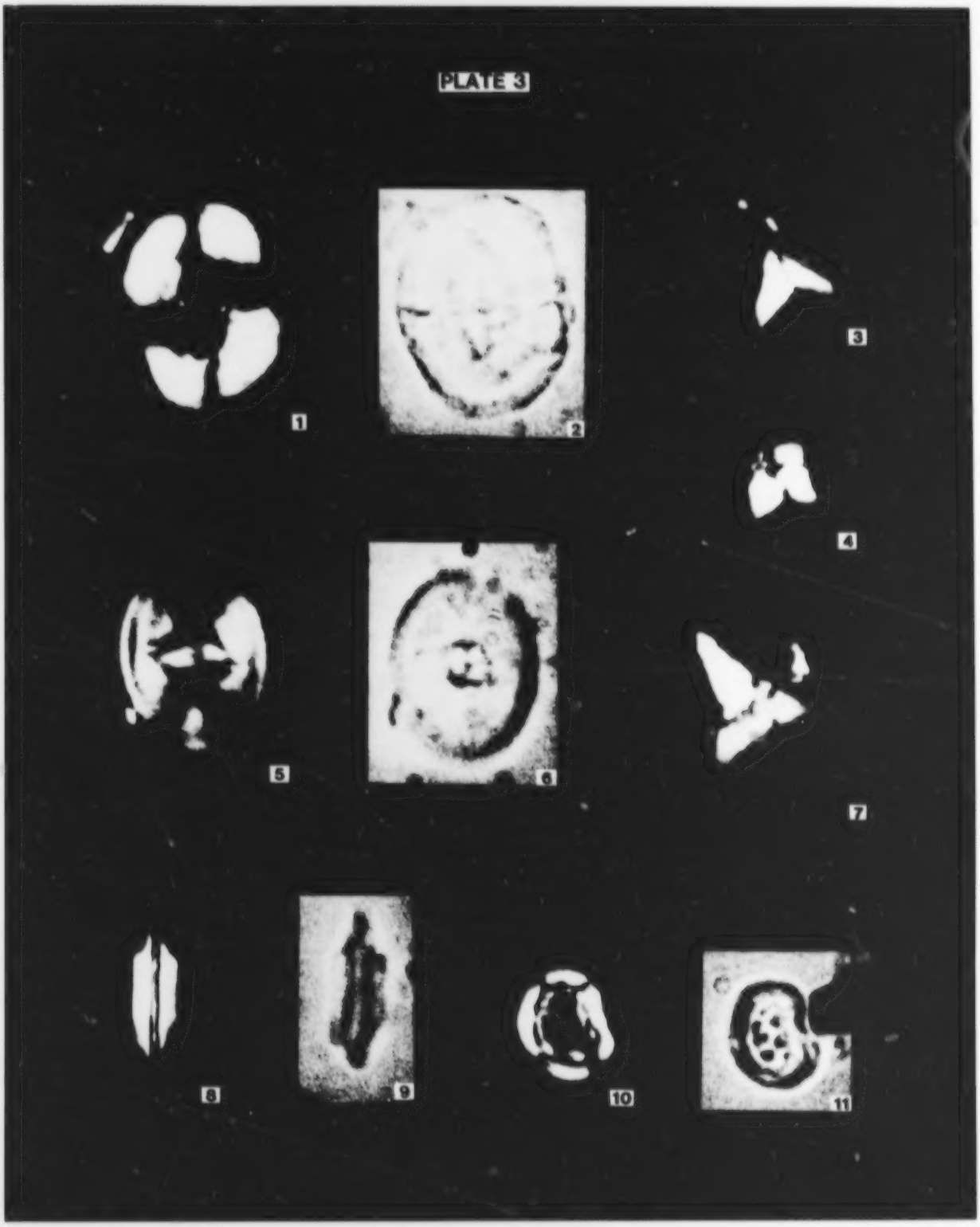
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PLATE 4

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Figures 1-2 *Watznaueria barnesae* (Black, 1959) Perch-Nielsen, 1968 Onondaga E-84, 3977 feet (*N. frequens* Zone)
1: Cross-polarized light
2: Transmitted light, same specimen as Figure 1

Figure 3 *Micula decussata* Vekshina, 1959 Onondaga E-84, 3977 feet (*N. frequens* Zone) Cross-polarized light

Figure 4 *Arkhangelskiella cymbiformis* Vekshina, 1959 Onondaga E-84, 3977 feet (*N. frequens* Zone) Cross-polarized light

Figures 5-6 *Kamptnerius magnificus* Deflandre, 1959 Onondaga E-84, 3977 feet (*N. frequens* Zone)
5: Cross-polarized light
6: Transmitted light, same specimen as Figure 5

Figure 7 *Lucianorhabdus cayeuxii* Deflandre, 1959 Cross-polarized light

Figure 8 *Phanulithus obscurus* (Deflandre, 1959) Wind and Wise, 1977 Mic Mac H-86, 2284 feet (*Q. trifidum* Zone) Cross-polarized light

Figure 9 *Phanulithus ovalis* (Stradner, 1963) Wind and Wise, 1977 Mohawk B-93, 2200 feet (Santonian) Cross-polarized light

Figures 10-11 *Lithastrinus grilli* Stradner, 1962 Mohawk B-93, 2500 feet (Coniacian)
10: Crossed-polarized light
11: Transmitted light, same specimen as Figure 10

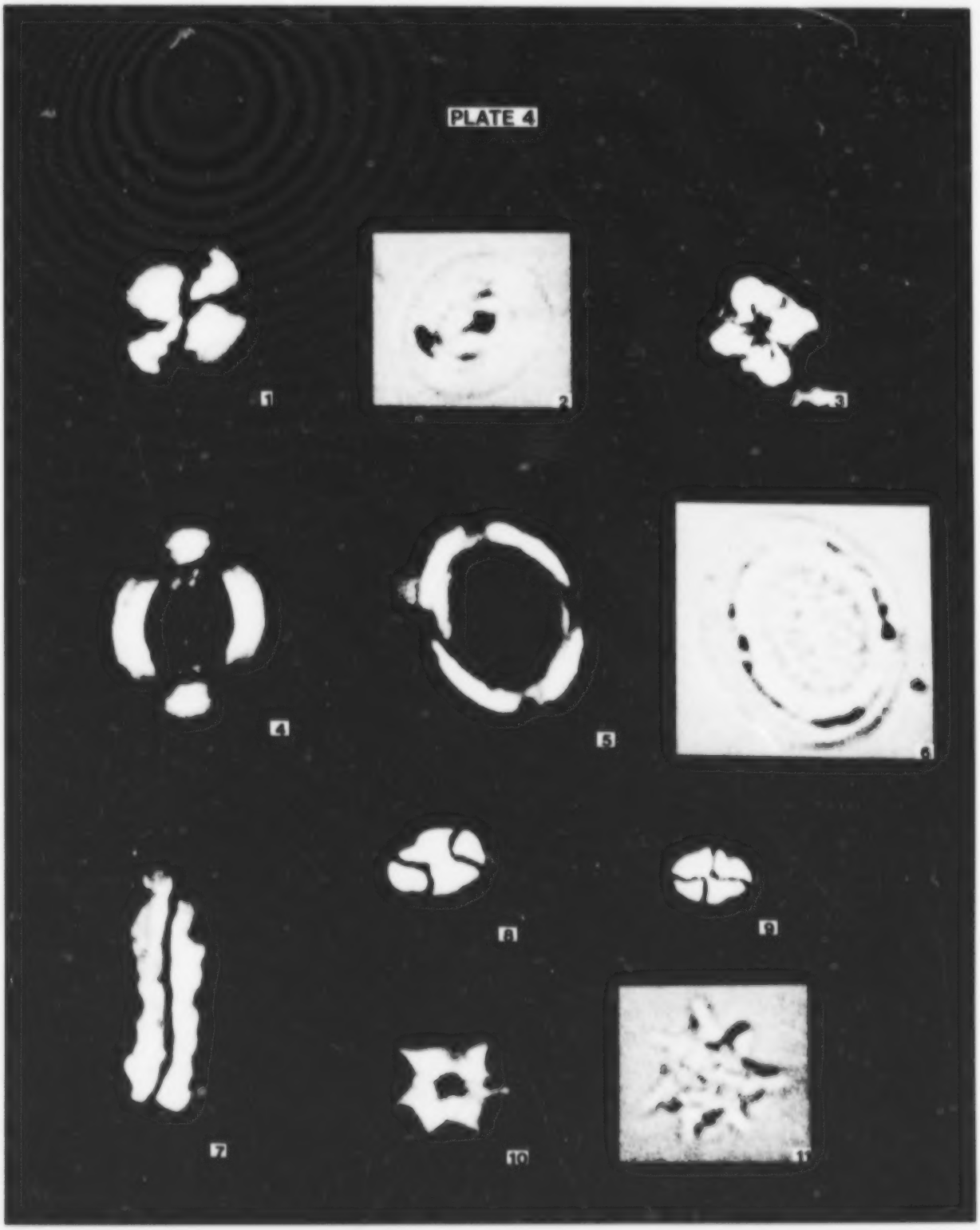
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PLATE 5

All figures x3200

Figures 1-4 *"Tetralithus" copulatus* Deflandre, 1959 Missisauga H-54, 3085-3317 feet (*Q. trifidum* Zone)

1: Distal view, high focus; cross-polarized light
2: Distal view, high focus; transmitted light, same specimen as Figure 1
3: Distal view, low focus; cross-polarized light, same specimen as Figure 1
4: Distal view, low focus; transmitted light, same specimen as Figure 1

Figures 5-8 *"Tetralithus" copulatus* Deflandre, 1959 Adolphus D-50, 9148 feet (*Q. trifidum* Zone)

5: Proximal view, high focus; cross-polarized light
6: Proximal view, high focus; transmitted light, same specimen as Figure 5
7: Proximal view, low focus; cross-polarized light, same specimen as Figure 5
8: Proximal view, low focus; transmitted light, same specimen as Figure 5

Figures 9-12 *Broinsonia* ex gr. *furtiva-lacunosa* Mohawk B-93, 2200 feet (Santonian)

9: Cross-polarized light
10: Transmitted light, same specimen as Figure 9
11: Cross-polarized light
12: Transmitted light, same specimen as Figure 11

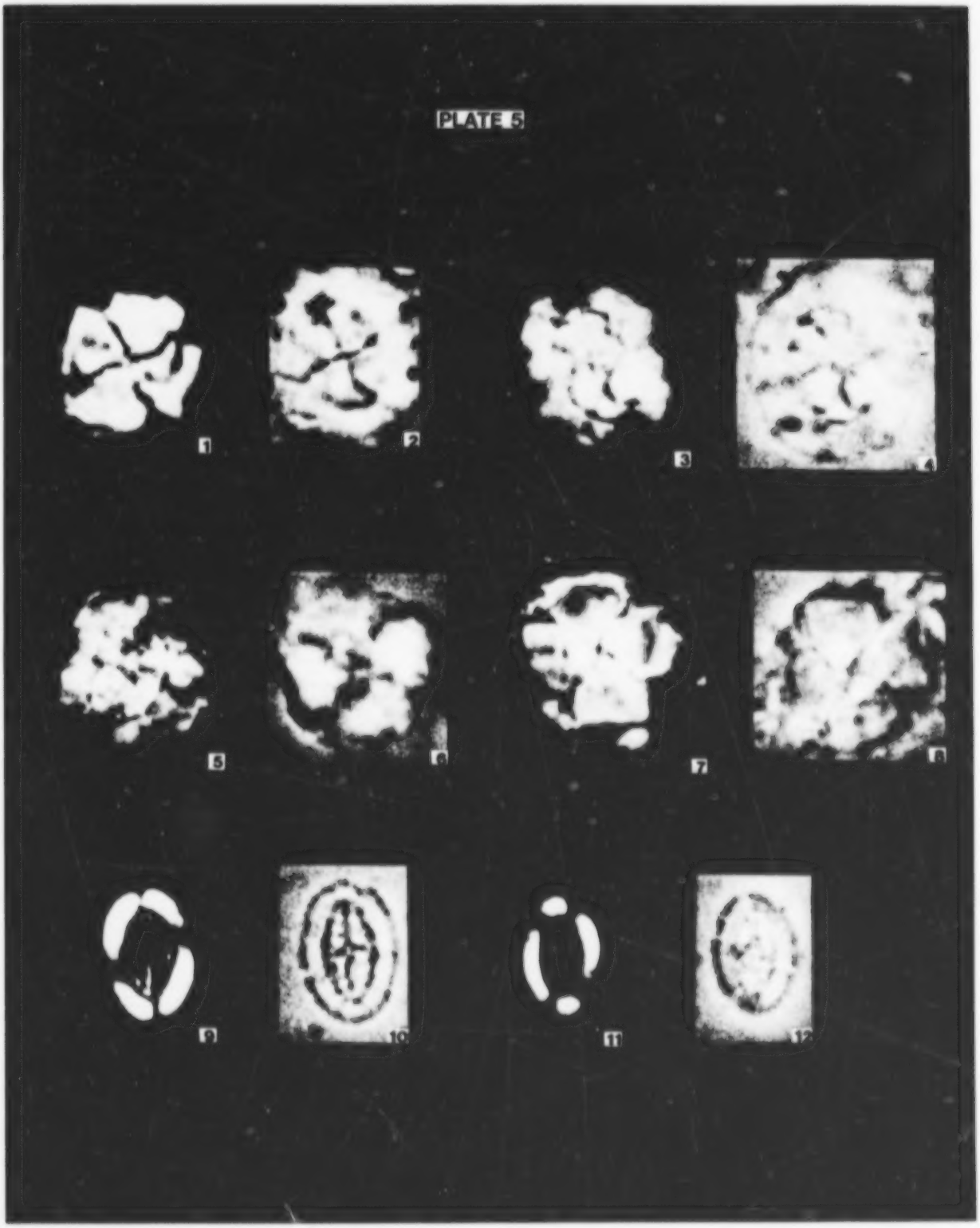
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PLATE 6

All figures x3200

Figures 1-3 *Lithraphidites* sp. aff. *L. quadratus* Bramlette and Martini, 1964 Primrose A-41, 5330 feet (*L. acutum* Zone, lower part)
1: Cross-polarized light
2: Cross-polarized light
3: Transmitted light, same specimen as Figure 2

Figure 4 *Lithraphidites* sp. Primrose A-41, 5330 feet (*L. acutum* Zone, lower part) Cross-polarized light

Figures 5-6 *Lithraphidites quadratus* Bramlette and Martini, 1964 Onondaga E-84, 4120 feet (*L. quadratus* Zone)
5: Cross-polarized light
6: Transmitted light, same specimen as Figure 5

Figures 7-8 *Lithraphidites carniolensis* Deflandre, 1963 Mohawk B-93, 2500 feet (Coniacian)
7: Cross-polarized light
8: Transmitted light, same specimen as Figure 7

Figures 9-10 *Lucianorhabdus* sp. 2 Mohawk B-93, 3662 feet (*L. acutum* Zone, upper part)
9: Cross-polarized light
10: Transmitted light, same specimen as Figure 9

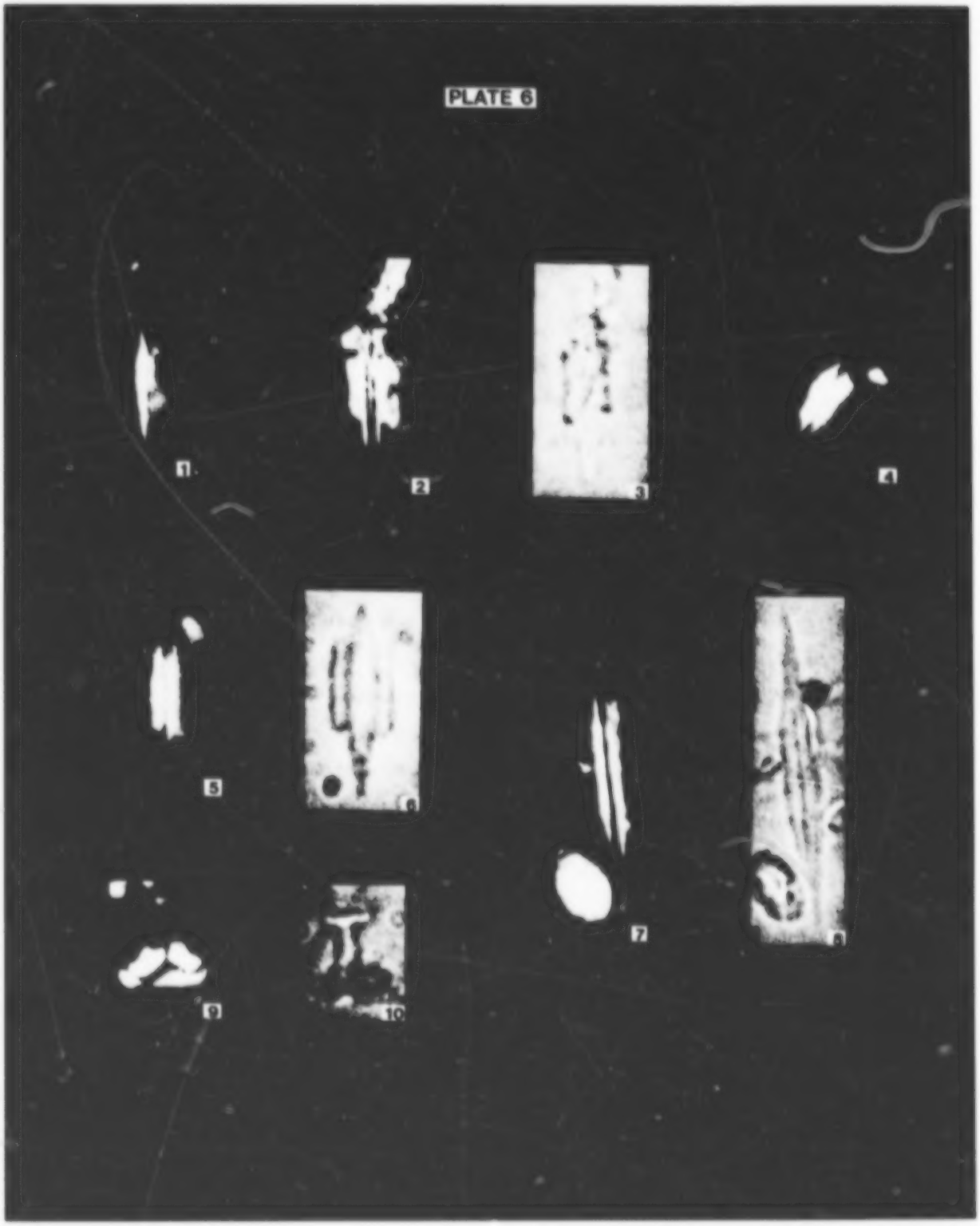
PLATE 6
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ERRATA

p. 5 right column last para., 2nd line should read "... *E. turriseiffeli* Zone ..."

p. 7 left column 1st heading should read "*Lithraphidites* ..."

p. 8 right column heading should read "*Rucinolithus hayii* Zone ..."

p. 9 left column 5th line from bottom delete "and" to read "... occurrence of *Q. trifidum* below the lowest occurrence ..."
right column 2nd last para. last line "*Lithraphidites quadratus* Zone."

p. 10 left column 6th line under Remarks should read "*Ceratolithoides kamptneri* ..."
line 14 should read "... of the *N. frequens* Zone."

p. 12 right column 11th line should read "*Podorhabdus* ..."

p. 16 left column 3rd line should read "... *Lithraphidites acutum* Zone ..."

p. 23 left column 2nd last para, 3rd line, and last para. 1st and last line should read "... *cushmani* ..."

p. 23 left column last para., 3rd line and right column 1st para, last line should read "... *Lithraphidites acutum* Zone ..."

p. 27 left column 6th last line should read "The *G. elevata* Zone ..."

p. 27 right column last para. 6th line should read "... *cushmani* ..."

p. 29 left column 3rd para. 10th line should read "... *frequens* Zone ..."

p. 37 left column 2nd para. 4th last line should read "... *frequens* Zone ..."

p. 39 Fig. 22 caption – 2nd line should read "*M. decussata* ..."

p. 40 Table 9 caption should read "... *frequens* Zone ..."

p. 48 left column *Broinsonis lacunosa* should read *Broinsonia lacunosa*

In the Appendix on p. 37 the correct entries are:

L. praequadratus Roth

R. cf. *miniporus* (Reinhardt and Gorka, 1967), Verbeek, 1977

Watznaueria barnesae (Black in Black and Barnes, 1959) ...

POOR

QUALITY

ORIGINAL